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Do Forest-Management Plans and FSC Certification Help Avoid Deforestation in the Congo Basin?

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Abstract

To allow for the production of timber while preserving conservation values, forestry regulations in the Congo Basin have made Forest Management Plans (FMP) mandatory in logging concessions. This paper uses original high-resolution maps of forest-cover changes and official records on the activities of logging concessions to analyze the impact of FMP on deforestation in this region. We apply quasi-experimental and difference-in-difference approaches to evaluate the change in deforestation in concessions managed under an approved FMP. We find that between 2000 and 2010, deforestation was 74% lower in concessions with an FMP compared to others. Building on a theory of change, further analyses revealed that this decrease in deforestation takes time to occur and is highest around communities located in and nearby logging concessions, and in areas close to previous deforestation. These findings suggest that FMP help avoid deforestation by allowing logging companies to rotate cycles of timber extraction, thereby avoiding the overexploitation of areas that were previously logged, and by the better regulation of access to concessions by closing former logging roads to limit illegal activities such as shifting agriculture, hunting and the illegal harvest of timber or fuel-wood.

Keywords: AFD, Forest management plan, FSC certification, deforestation, quasi-experimental matching, causal mechanisms, Congo Basin

JEL Classification: C21, Q23, Q56, Q58

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1 Introduction

About 400 million hectares of natural tropical forest are devoted to timber production (Blaser et al., 2011). Ensuring the sustainable exploitation of these forests is a crucial challenge, as they are a key factor for biodiversity, carbon sequestration and the global climate. In the Congo Basin, the second-largest tropical forest after the Amazon, with an area of about 178 million ha of dense humid forests (Mayaux et al., 2013), almost one third of forests are productive in terms of logging exploitation. Hence, national forestry regulations have made Forest Management Plans (FMP) mandatory in logging concessions to ensure the sustainable exploitation of these forests. In principle, the FMP seek sustainable timber production that limits deforestation and guarantees the preservation of forest resources, biodiversity and ecosystem services, while contributing to local socio-economic development (Nasi et al., 2012). FMP promote that the forestry operations are done with the least possible damage to the residual forest stand and allow forest regeneration, so that the logging companies can return to the same area after one rotation – usually 25 to 30 years – and harvest again (Bertrand et al., 1999a,b; Fargeot et al., 2004). For these reasons, and because of the extent of forest areas covered, FMP are often considered as a major contribution to tropical forest conservation worldwide, and have been supported by international organizations and non-governmental organizations (NGO) (Clark et al., 2009; Lambin et al., 2014). However, in practice, the design and implementation of FMP have been very heterogeneous among countries and logging concessions (Cerutti et al., 2008) and the question of FMP sustainability is still under debate (Brandt et al., 2016, 2018; Karsenty et al., 2017).

From that perspective, the theoretical impact of FMP on deforestation is ambiguous and there is relatively scant empirical work that document the extent of forest cover change in logging concessions with an FMP. Cerutti et al. (2017) showed that FMP in Cameroon between 1998 and 2009 effectively reduced carbon emissions from logging operations due to the reduced volumes of timber harvested, as imposed by the FMP, while presenting logging companies with acceptable financial trade-offs. In contrast, Brandt et al. (2016) found that concessions with FMP in the Congo, compared to otherwise similar concessions without, were associated with greater deforestation. Further analyses suggested that, greater timber production driven by increased foreign capital and international demand contributed to greater deforestation in the six concessions with FMP in the Congo (Brandt et al., 2016, 2014). This led to a controversy between Karsenty et al. (2017) and Brandt et al. (2018), emphasizing the need for more empirical work to understand whether and under which conditions FMP affect deforestation.

While there is a paucity of work on the effects of FMP, somewhat more attention has been given to Forest Stewardship Council (FSC) certification: a voluntary market-based approach which goes beyond the approval of FMP by national forestry regulators and promotes a responsible management of the world's forests certified by a third non governmental party. With a wide range of social and environmental issues covered by FSC standards, avoiding tropical deforestation remains a central FSC objective, and a number of empirical contributions have looked at the impact of FSC certification on deforestation (e.g. Blackman et al., 2018; Heilmayr and Lambin, 2016; Miteva et al., 2015; Panlasigui et al., 2018; Rana and Sills, 2018; Rico et al., 2018). Komives et al. (2018) provide a thorough review of the studies that present the most convincing evidence of the effects of FSC certification on deforestation and concluded that, with the exception of Heilmayr and Lambin (2016), the emerging body of studies (i.e. Blackman et al., 2018; Panlasigui et al., 2018; Rico et al., 2018) provides increasing evidence of non-impact of FSC on measured rates of forest-cover change. Though Heilmayr and Lambin (2016) found that FSC certification effectively reduced deforestation in Chile, studies in Cameroon (Panlasigui et al., 2018) and Peru (Rico et al., 2018) have found small effects ($< 0.1\%$) of FSC certification on reduced deforestation, and Blackman et al. (2018) found no significant impact of FSC on forest cover loss in Mexico.

Since FMP and FSC certification promote sustainable management of the logging concessions over longer time horizon, other studies argued that, like land zoning, they protect the forest from competing uses that encourage deforestation (Angelsen, 2010). Bruggeman et al. (2015) tested that prediction in Cameroon and found that, compared to forest outside zoning, deforestation rate was smaller in logging concessions.

Overall, documenting the impact of FMP and FSC on deforestation in the Congo Basin is an active research area. The results from similar policy interventions in Asia and South America suggest that the effects are weak, context-dependent, and could therefore not be reproduced in different settings. As reducing deforestation in low-income countries is arguably one of the most cost-effective ways of reducing global CO_2 emissions (Barker et al., 2007; Stern, 2006), this paper seeks to evaluate the average effect on deforestation of the legal requirement that concessions across countries in the Congo Basin have an approved FMP. More particularly, we check whether approval of FMP by national forestry regulators affects deforestation within concessions with FMP. However, since approval of an FMP does not necessarily imply its effective implementation (Cerutti et al., 2008; Karsenty et al., 2017), our study does not provide a measure of the average effect of the implementation of FMP on deforestation. Conversely, logging concessions with FSC certificate are more likely to implement their FMP. Hence, we also document the average effect of FSC certification on deforestation in concessions with FSC certificates in the Congo Basin, and study some of the underlying mechanisms explaining whether and how FMP work (Baylis et al., 2016; Miteva et al., 2012).

To provide an empirical estimate of the impact of FMP approval and FSC certification in the Congo Basin, we use original high-resolution maps of forest cover change in Cameroon, Congo, Gabon and the Central African Republic (CAR) over the 1990-2000 and 2000-2010 periods. The geographic area does not include the Democratic Republic of Congo, where FMP were initiated later. The deforestation maps are complemented with relevant detailed information on the location and extent of logging concessions, including the timing of the official approval of their FMP and FSC certification. To estimate the impact of FMP approval and FSC certificates, we use quasi-experimental methods whereby the logging concessions with approved FMP or an FSC certificate issued before 2010 are compared to their peers that had not approved their FMP yet but had otherwise similar observable characteristics known to affect deforestation.

Even though the concessions with approved FMP or an FSC certificate in the Congo Basin were not randomly chosen, the approach used in this work will likely produce unbiased estimates of forest cover change within concessions that is attributable to FMP approval or issuance of FSC certificate for at least two reasons. First, since the 1990's, Cameroon, Congo, CAR and Gabon have all implemented reforms mandating logging companies to adopt FMP (Karsenty, 2007). FMP were then gradually implemented in the 2000s, albeit in a context of uncertain incentives and environmental governance. By 2010, one-third of the concessions in the study area had an accepted FMP. FSC certification is more recent in the region, starting only in 2005. In this context of slow but progressive production and approval of FMP and imperfect compliance with forestry law, it is likely to match otherwise-similar concessions with and without FMP, which is a key requirement for unbiased quasi-experimental analysis. Second, even though national policies aiming to impose FMP adoption have been discussed since the 1990s, the first logging concessions with FMP appeared in the early 2000s in the Congo Basin. Since we can also measure deforestation between 1990 and 2000, we fine-tune our estimates of the FMP impact on logging concessions by correcting for pre-existing differences in deforestation rates between early and late FMP adopters in the Congo Basin. Last, we test the robustness of the results and replicate our analysis using the widely-used Global Forest Change (GFC) dataset (Hansen et al., 2013) over the 2000-2010 period. By doing so, we add to existing empirical work on the impact of FMP on deforestation by considering a large sample of logging concessions covering the whole Congo Basin – except the Democratic Republic of Congo (DRC).

The remainder of the paper is organized as follows. In Section 2 we present background information on FMP and the theoretical framework behind their potential deforestation effects in the Congo Basin. Section 3 then describes the main datasets used, and Section 4 outlines the empirical strategy used to explore the causal impact of FMP on deforestation. Section 5 presents the main results, their robustness to methodological choices, then explores the channels underlying the link between FMP and deforestation. Last, Section 6 discusses the limitations and implications of our work before offering some concluding observations.

2 Background and theoretical framework

In the Congo Basin, most forested areas are State-owned, and exploitation permits are granted to private logging companies for periods of 15 to 30 years (except for CAR where logging permits can span over a 100-year period) under concession regimes, providing long-term resource-extraction rights in exchange for a stream of revenues (Agrawal et al., 2008). In this context FMP, if properly designed and implemented, could be considered as a tool for sustainable forest management, combining timber production, local development and conservation values in the Congo Basin (ATIBT, 2007).

2.1 Forest-Management Plans in the Congo Basin

FMP in a concession involve a range of environmental and social issues. In theory, FMP evaluate the potentialities of the resource and assess the trade-offs among the ecological, economic and social aspects of forest management to propose balanced options (Cerutti et al., 2017). For this, they are based on forest inventories describing the distribution of tree species and their characteristics. Associated with ecological and social studies (e.g., on fauna and on the forest uses of local communities), these inventories allow dividing each concession into *management series* areas according to different objectives of forest resources uses.

The *production series* are divided into *annual cutting areas*, for which the FMP presents a detailed plan for selective logging over a specific time period. This plan aims to optimize the exploitation of timber, while ensuring the partial regeneration of forest species in order to guarantee the viability of the next logging cycle (the usual rotation time is between 25 and 30 years). The *conservation series* are areas protected from logging activities and designed to preserve seed trees and the most vulnerable areas like steep slopes and riversides. Concerning local communities, logging companies need to engage with communities in and around the concession to ensure the coexistence of different forest uses and to encourage them to carry out sustainable natural-resource management, in particular regarding hunting and agriculture. Where villages are included inside concessions, *community-management* series are defined (ATIBT, 2007; Nkeoua, 2003). Moreover, for local development, forestry laws impose to logging companies specific forest taxation and services development such as building wood-processing facilities (sawmills) that employ local workers. In addition to that, FMP require that logging companies prepare and sign "social contracts" (*cahier des charges*), which define the terms of benefits redistribution and investments for local infrastructure (ATIBT, 2007). Finally, FMP include reduced-impact logging (RIL) practices and facilitate checks on operating activities by regulators (Cerutti et al., 2008; Ezzine de Blas and Pérez, 2008; Karsenty et al., 2008; Putz et al., 2008b).

In all of the Congo Basin countries except the CAR,[1] the FMP is elaborated by the logging company on the basis of national standards and under the control of forest administrations. After the attribution of forest concessions, logging companies can start logging immediately but have to prepare their FMP within a maximum of three years. The FMP is then reviewed by the forest administration, which evaluates the quality of the plan and either approves it or sends it back to the company with a request for review. In practice, this three-year period is poorly-respected.[2] Moreover, FMP may not deliver the expected outcomes. First, logging companies are responsible for the drafting of the FMP, which will therefore correspond to the one which best fit their strategy: the FMP proposed by the owner of the logging concession will reflect the relative weight they put on conservation and economic outcomes (Cerutti et al., 2017). Second, the fact that an FMP has been officially-approved is neither a quality guarantee nor an indication of its effective implementation on the ground (Cerutti et al., 2008; Karsenty et al., 2017).

[1]The CAR is the only country in the Congo Basin where a public structure carries out the FMP for logging companies, mainly because the CAR has since 2000 benefited from a support project for the implementation of FMP (the PARPAF project financed by the AFD).

[2]The database of the World Resource Institute on the attributes of logging concessions in the study area estimates that there is on average 9 years between the date when the exploitation permit is issued and the approval date of the FMP. Moreover, only 5% of logging concessions have received an approved FMP less than 3 years following the issuance of their exploitation permit.

2.2 FSC certification to enhance efforts toward sustainable forest management

To show their commitment toward sustainable forest management, logging companies with an approved FMP can apply to voluntary certification schemes such as the Forest Stewardship Council (FSC). This is a voluntary, market-based approach to enhancing sustainable forest management. In FSC certified concession, logging companies commit to comply to FSC standards, which aim to promote "environmentally appropriate, socially beneficial and economically viable management of the world's forests" (FSC, 2019). In return, the FSC label on the forest's products is expected to be beneficial in terms of market access and share, and higher prices (Romero et al., 2017). For certification, logging companies commit to adhere to the ten international FSC principles and twelve criteria, covering social aspects such as workers' rights and employment conditions, and environmental aspects, including diverse measures of forest-management planning and monitoring similar to those that are supposed to appear in their FMP. Independent certifying bodies audit concessions prior to certification to determine their conformity to the FSC criteria: they then provide certificate for five years, during which they carry out annual concession inspections to ensure their continued compliance (FSC, 2019).

In the context of institutions in developing countries, where regulators have limited resources to enforce compliance to Forestry Law and FMP, this third-party verification should provide additional guarantees that logging companies have effectively adopted sustainable forest-management practices and respect their FMP in their certified concessions (Blackman et al., 2018). For this reason, regarding the environmental aspects of forest management, the added value of the FSC is mainly to avoid FMP that only reflect economic criteria or apply only on paper, with few, or no, measures implemented in practice.

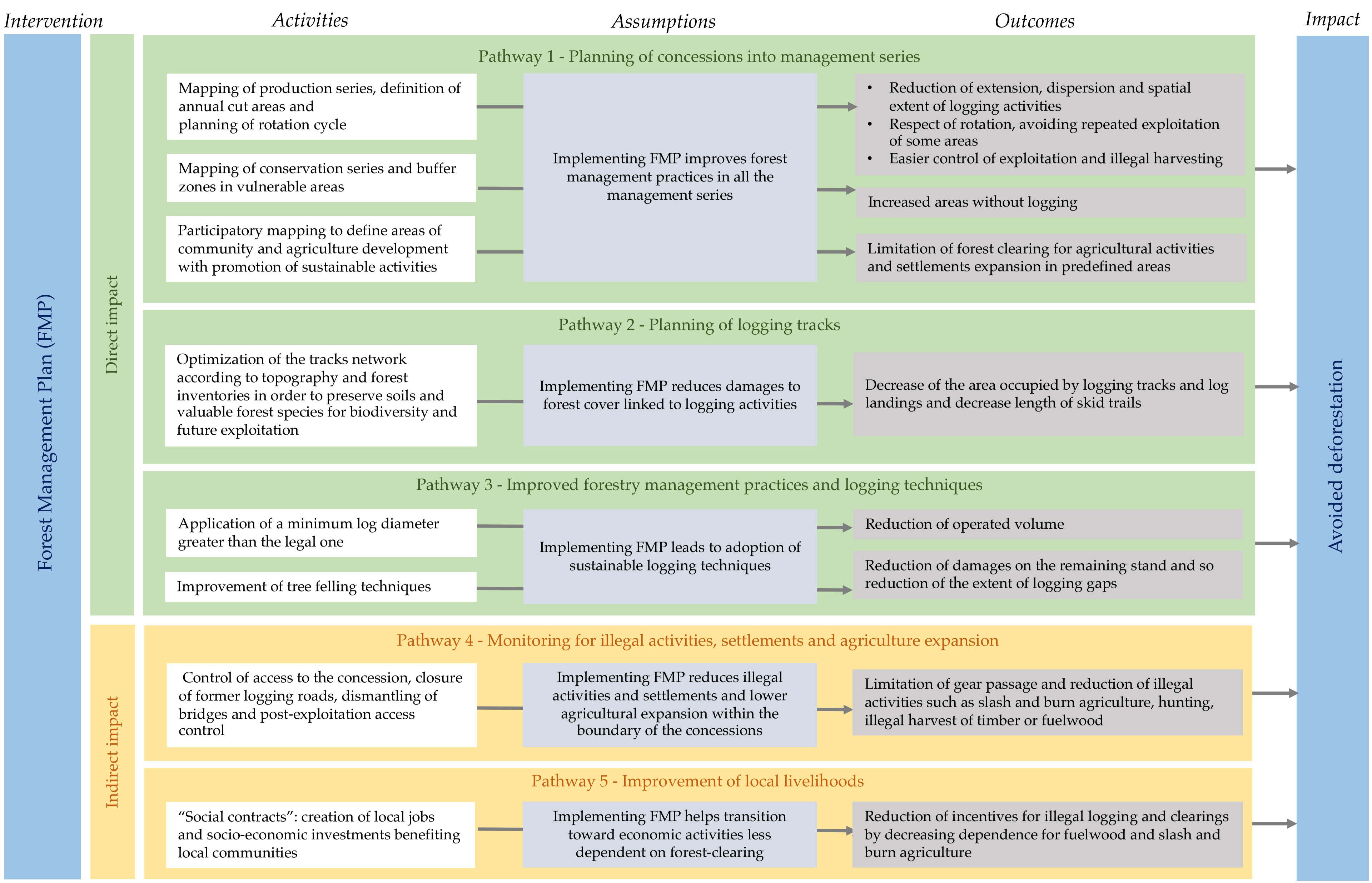
2.3 Theory of change

To mitigate climate change, Governments of Cameroon, CAR, Congo and Gabon intend to promote forest management plans to reduce GHG emissions from logging companies (see République du Congo, 2015; République Centrafricaine, 2015; République du Cameroun, 2016; République Gabonaise, 2015). Given the extent of forest areas covered by logging companies, we seek to document whether promoting approval of FMP in the Congo Basin is on average an effective mean to reduce emissions from deforestation in the region. Since FMP and FSC certification objectives are much broader than reducing deforestation, we build a model of how these interventions are expected to affect deforestation (e.g. Blackman et al., 2018; Meyfroidt et al., 2018; Romero et al., 2017; Romero and Putz, 2018) and measure the average effect of FMP approval on deforestation in the Congo Basin. Figure 1 summarizes the theory of change through which we hypothesize that FMP and FSC certification could reduce deforestation in logging concessions.

Five main causal pathways relating forest management to deforestation are identified. Three of them are directly under the control of the logging companies: (i) planning of concession through the creation of management series; (ii) planning of logging tracks, log landings and skid trails and (iii) improved forestry-management practices and logging techniques. The next two are *indirect pathways* linked to third person activities: (iv) monitoring of the concession for limiting the expansion of settlement, agriculture and illegal activities; and (v) improvement of the livelihoods of local communities. In a context of imperfect governance, it is likely that what remains under the company direct control is more likely to be implemented than what the company does not have under its direct control. Moreover, as discussed below, these different pathways implicitly assume various time horizons applicable to the theoretical impacts which are detailed above (ATIBT, 2007; Cerutti et al., 2017; Ezzine de Blas and Pérez, 2008; Putz et al., 2008a).

First, FMP should allow logging companies to plan their activity over time and space:

Figure 1: Theory of change



through the forest inventories, they can divide their concession into production and conservation series. Moreover, participatory mapping activities with local communities should help identify the areas of the concession devoted to community development and small-scale agriculture (ATIBT, 2007). These activities could help reduce deforestation in different ways. In production series, rotation planning and the definition of annual cut areas should reduce the expansion, dispersion and sprawl of logging activities, while ensuring that the forest remains undisturbed between exploitation cycles, thereby reducing the repeated exploitation of the same areas. In addition, the definition of conservation series and buffer zones in more vulnerable areas should increase the area that is not logged – thus without new logging roads and logging disturbance (e.g. Durrieu De Madron et al., 2011). Last, in concessions that are inhabited and provide livelihood to local populations, the definition of community-management series should limit forest clearing for agricultural activities and settlement expansion in predefined areas (ATIBT, 2007).

Second, FMP should include the planning of logging tracks, log landings and skid trails. The main activity here should be the planning and optimization of the track network according to the topography, forest inventories and the location of annual cut areas in order to preserve soil and valuable forest species for biodiversity and future exploitation. The outcomes are to reduce or optimize the areas affected by logging tracks, log landings and skid trails. This is expected to reduce deforestation and the damage to forest cover linked to logging, at least on the longer-term (e.g. Durrieu De Madron et al., 2011).

Third, FMP should include the adoption of a set of improved forestry-management practices and logging techniques such as: (i) the application of a minimum log diameter (over the legal minimum) that should reduce the volume of timber harvested and the pressure on the most-valuable species and (ii) the improvement of tree-felling techniques (controlled or directional tree felling) which should limit the damage to the remaining stand linked to tree fall and skidding manoeuvres. These practices are mostly expected to reduce forest degradation, but should also, to a lesser extent, reduce deforestation by preventing large canopy gaps and tree-felling in sensitive areas that may require long recovery times (Peña-Claros et al., 2008; Pearson et al., 2014; Putz et al., 2008b).

Fourth, FMP should include concession monitoring in order to control the expansion of settlements and agricultural areas, as well as illegal activities. This should include activities for controlling concession access: the temporary or permanent closure of logging tracks, the dismantling of bridges and post-exploitation access control. This monitoring is expected to limit gear passage and to reduce illegal activities such as slash and burn agriculture, hunting and the illegal harvesting of timber or fuel-wood, which could produce deforestation through forest clearing, repeated forest exploitation or even fire spread (Kleinschroth et al., 2016a,b).

Finally, through the associated social and local development measures, FMP could enhance the livelihoods of those who live and work in and around logging concessions. Improved livelihoods in turn may reduce the incentives for both illegal and unsustainable logging, and could also reduce clearings by reducing the dependence on fuel-wood and slash and burn agriculture. However, the relationship between livelihoods and deforestation is complex and, in some cases, improved livelihoods may spur forest-cover change or attract more people (Chomitz and Buys, 2007; Rist et al., 2012), potentially increasing deforestation (Blackman et al., 2018).

FSC certification should affect deforestation through the same five causal mechanisms as noted above. In addition, FSC certification includes monitoring by independent certifying bodies that assess whether forest management practices comply with FSC standards (see Romero et al., 2017). These audits should also further enhance monitoring of activities of logging companies by NGO and the media (Blackman et al., 2018). In the context of weak capacity of local governance, the activities of certifying bodies, environmental NGO and the media should result in better implementation of each of pathways outlined above. Hence, to the extent that the enforcement of FMP practices by local regulators in the study area is weak, we may expect that FMP are more likely to be enforced in concessions with an FSC certificates, and find a greater fall in deforestation on the longer term in concessions that are FSC-certified.

By their nature, these mechanisms are likely to produce effects over different time frames and in distinct areas inside concessions. At first, the planning and monitoring of concessions, as well as improved livelihoods, would likely produce effects that are visible in the short to medium term, mainly in areas close to settlements, the main transport networks and previously-opened logging roads. Second, the adoption of improved forestry-management practices and logging techniques is expected to affect the forest in production series by allowing valuable trees to regenerate, which is expected to produce effects on observable deforestation mostly in a longer time frame. In the same longer time frame, the planning of logging tracks and log landings is expected to affect the forest in production series through the enforcement of annual cut areas. For these reasons, the impact of FMP or FSC certification on deforestation should vary over both time and space within concessions.

Since FMP and FSC certification aim at other objectives than avoiding forest cover loss, it is worth noting that their implementation may often present trade-offs with ambiguous effects on deforestation (e.g. Romero et al., 2013). For example, in some circumstances, it might be optimal for a company to allow for efficient access by creating a permanent road network through a concession. While constructing such road network creates forest cover loss on the short term, it will allow the company to rotate timber extraction across production series and may have beneficial effect on deforestation on the longer term. The deforestation induced by road networks should also be reversed as forest are resilient and regenerate along former logging roads (see ecological studies by Gourlet-Fleury et al., 2013; Kleinschroth et al., 2016a,b). Other examples of trade-offs include the temporary deforestation linked to logging gaps: large canopy openings may be needed for some shade-intolerant species to regenerate and, hence, may not be inconsistent with sustainable forest management, even if the deforestation may be higher initially. For these reasons, the theoretical impact of FMP on deforestation is ambiguous and warrants closer empirical investigation. While we seek to disentangle the effect of FMP according to different time-frames, we will not be able to distinguish between permanent and temporary deforestation and do not explore the trade-offs discussed above.

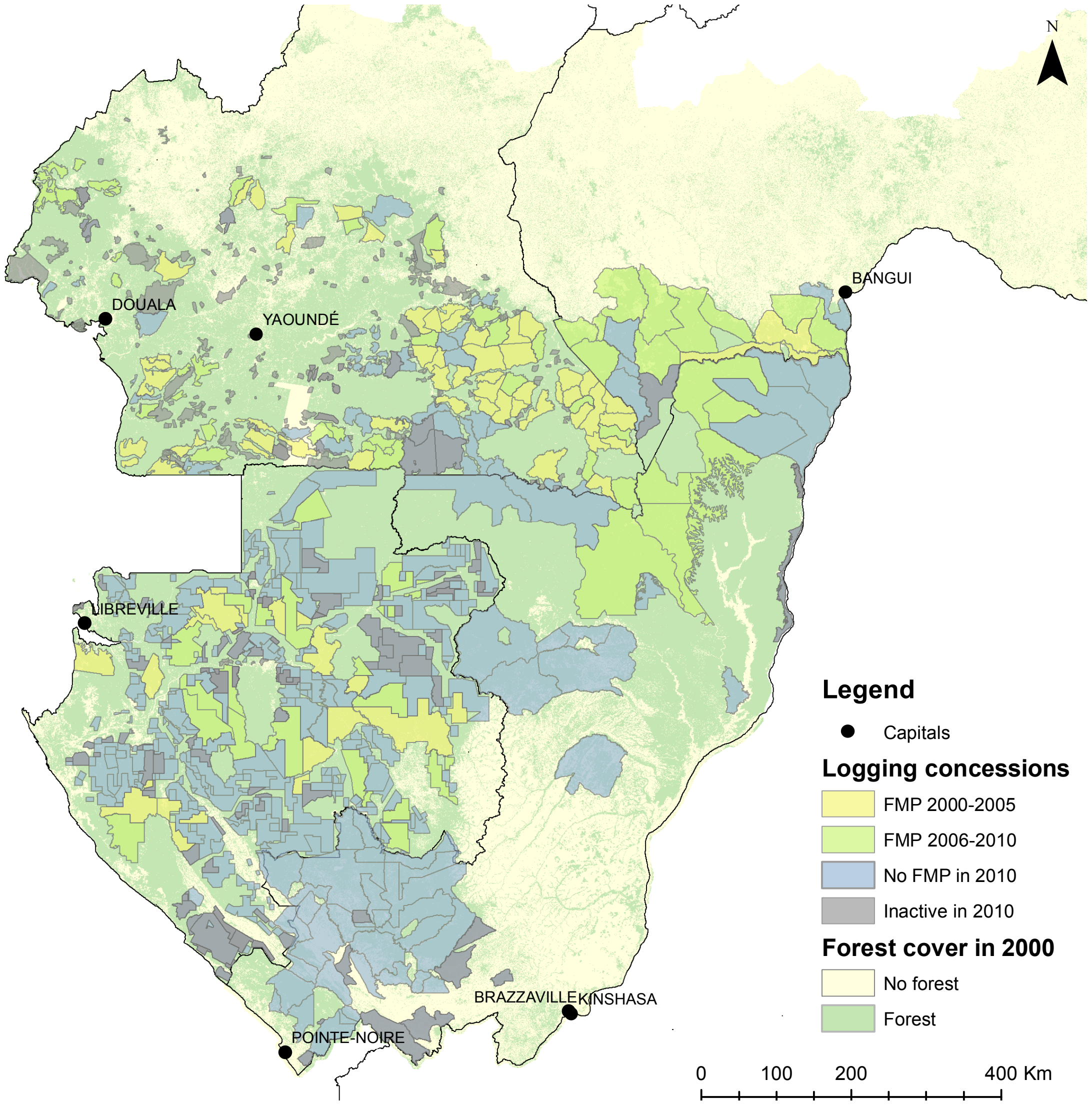
3 Data

We use two types of information to evaluate the effect of FMP and FSC certification.

We initially collected detailed information on logging concessions in the study area using the official land-tenure data released by the Central African Forest Observatory (OFAC) and World Resources Institute (WRI) in the "Congo Basin Forest Atlases". The dataset covers 397 concessions across the four countries under consideration (see Figure 2) and was updated using the gray literature and information collected on the ground from local actors, especially in the case of concession reallocation to another logging company during the study period.

The database includes no reliable information that consistently documents the volume of timber extracted each year at the concession level in the study area. Thus, we used the date of issuance of the exploitation permit to identify when a concession is active. Likewise, we do not observe whether a logging concession is implementing an FMP. However, we have detailed information on the date when the FMP of a given concession was approved and used it to identify logging concessions with an approved FMP. Since approval of an FMP does not necessarily imply its implementation, the average effect of FMP approval, our measure of interest, is likely to underestimate the average impact of the implementation of FMP in the Congo Basin. Indeed, even though deforestation decreases in concessions that implement their FMP, the effect of FMP approval can be null if most concessions with approved FMP do not effectively implement their FMP on the ground. Unlike possession of an approved FMP, issuance of FSC certificate identifies logging concessions whose practices have been verified and certified by an FSC-accredited external agent. Hence, we used the date of issuance of FSC certificate, to identify logging concessions that received their FSC certificate on time to

Figure 2: Location of concessions in the countries analysed in the Congo Basin



implement forestry practices likely to affect forest cover change during the observation period. Other information collected on logging concessions include the physical attributes of their environment (altitude, steepness and biomass), their area, and their proximity to road infrastructures and settlements, which can affect competition over forest resources and management decisions of logging companies (see Table S1 for detailed characteristics of active logging companies included in the study).

The second type of information consists of high-resolution maps of forest cover and forest-cover changes across the Congo Basin. The maps come from two sources. First, we used the original maps produced as part of the global effort to reduce emissions from deforestation and forest degradation in the Congo Basin (see, Fichet et al., 2012, 2014; Sannier et al., 2016, 2014). To quantitatively assess the spatial and temporal dynamics of forest change, the governments of Cameroon, CAR, Congo and Gabon developed national forest-monitoring systems (NFMS). As part of this effort, a number of remote-sensing projects were carried out in each of these countries in close collaboration with the administration in charge of forest monitoring. The resulting maps are based on high-resolution satellite imagery and ground-verification data, and should provide greater cartographic and thematic accuracy than global data (Sannier et al., 2016). Combining these data, we produced homogeneous regional-level maps of forest cover at three points in time (1990, 2000 and 2010) and calculated gross deforestation between these dates (see Table 1 and Figure S1). Second, for comparison purposes, we use measures of tree-cover loss produced from the Global Forest Change (GFC) dataset (1.0) (Hansen et al., 2013). We calculated tree-cover loss between 2000 and 2010 for two tree-cover thresholds, 30% and 70%. The 30% tree-cover threshold is that used in most forest definitions, but in the case of the countries of the Congo Basin, the 70% tree-cover threshold seems to be more realistic given the forest conditions on the ground (Sannier et al., 2016).

Table 1: Forest cover and forest-cover change in the study area.

Country	Period	Forest cover (km^2)	Deforested area (km^2)	Deforestation rate (%)
Congo	1990-2000	223 554	1 375	0.62
	2000-2010	233 595	1 911	0.82
Gabon	1990-2000	237 242	1 025	0.43
	2000-2010	236 634	512	0.22
Cameroon	1990-2000	245 396	4 790	1.95
	2000-2010	241 487	4 245	1.76
CAR	1990-2000	98 759	3 140	3.18
	2000-2010	96 364	2 632	2.73
Total	1990-2000	804 951	10 330	1.28
	2000-2010	808 080	9 300	1.15

Combining the map giving the location and geographical coverage of each logging concession and the existence of either an approved FMP or an FSC certificate to the high-resolution deforestation maps informs about the deforested area over 1990-2000 and 2000-2010 in each concession. However, the direct comparison of the area deforested to time of FMP-approval or FSC certificate-issuance is biased. Indeed, concessions with an approved FMP or an FSC certificate were not randomly drawn. Hence, compared to their peers that had not validated their FMP by 2010, the logging concessions with either an approved FMP or an FSC certificate delivered between 2000 and 2010 differ on many dimensions that are also known to affect deforestation (see Table S2). Therefore, a simple comparison risks attributing the effect of other observable or unobservable concession characteristics to approval of FMP. Moreover, in line with the theory of change, we would like to disentangle the effect of FMP for different time frames taking different definitions of treatment in function of the date of FMP approval.

The next section describes the empirical framework used to address this problem and select concessions based on the likelihood that the effects of their activities contribute to the deforestation measured over the observation periods. We then present the potential-outcomes framework of Rubin (1974) that we use to deal with potential confounders and estimate the deforestation effect of FMP.

4 Empirical framework

In line with the theory of change outlined above, we seek to evaluate the average effect of FMP-approval or issuance of FSC certificate on deforestation in concessions with approved FMP or FSC certificate. Furthermore, we will study how the average effect of the FMP approval changes across different time frames and look for spatial heterogeneity within and in the neighborhood of forest concessions. The analyses are carried out at the concession level. Hence, the main outcome of interest are measures of forest cover loss during two 10-year periods (1990-2000 and 2000-2010).

4.1 Treatment groups

The first logging company in the study area had its FMP approved in 1999. To document the average effect of FMP approval and FSC certification over different time frames, while allowing each comparison group to have adequate sample size, we focus on estimating the average the impact of (i) having an FMP approved between 2000 and 2005, (ii) having an FMP approved between 2006 and 2010 and (iii) obtaining an FSC certificate between 2000 and 2010 on deforestation between 2000 and 2010.

Since the potential effects of FMP on deforestation are more likely to appear over the medium to long run, we expect that deforestation between 2000 and 2010 will be lower in the concessions that have had an FMP approved for a longer period. In that vein, we have divided the observation period in half and distinguished between the concessions that received their FMP before 2005 (treatment *FMP 2000-2005*) and those that had an FMP approved between 2006 and 2010 (treatment *FMP 2006-2010*).[3] Since deforestation is measured between 2000 and 2010, treatment *FMP 2006-2010* reflects the immediate to very short-term impacts of FMP approval. Indeed, those treated concessions have had their FMP approved for at most four years. In contrast, treatment *FMP 2000-2005* include concessions that have had their FMP approved for at least five years between 2000 and 2010 and will help measure the short to medium-term impacts of FMP approval.

In both of these two treatments, the control group is composed of active concessions without an approved FMP. We define a concession as *active* if it was attributed to a logging company for at least two years for the *FMP 2006-2010* treatment (i.e. since 2008) and at least five years for the *FMP 2000-2005* treatment (i.e. since 2005, in order to be consistent with the treated concessions that, by definition, have all been active since 2005). Therefore, the concessions with no approved FMP (the *No FMP concessions*) include all the active concessions that had no FMP approved by 2010 (in 2005, respectively, for the *FMP 2000-2005* treatment), including concessions with FMP approved

[3] Very few concessions had an accepted FMP in 1999 and our data do not allow us to measure the impact of FMP over longer time periods.

after 2010. For the *FMP 2000-2005* treatment, concessions that had an FMP approved between 2005 and 2010 were excluded.

Overall, there are 60 concessions with an FMP approved before 2005 and 165 no-FMP concessions for the FMP 2000-2005 treatment and 61 concessions and 194 no-FMP concessions for the FMP 2006-2010 treatment. With the first certificates issued in 2005, FSC certification is recent in the Congo Basin. Consequently, we can only estimate the average short term impact of FSC certification (after one to five years of certification) on 2000-2010 deforestation (treatment *FSC 2000-2010*). It is also worth noting that all FSC-certified concessions already had an approved FMP. Since concessions with FSC certificates are more likely to implement their FMP, measuring the impact of issuance of FSC certificate between 2005 and 2010 on deforestation also provides information on the average impact of implementing FMP in concessions with FSC certificates. Though the FSC-certified concessions have had a certificate over a short period, most of them had an FMP approved before 2005. Hence, the average effect of FSC-certificate is measured for a group of logging concessions that have had their FMP approved for at least five years and have received a third-party verification of their practices by an FSC-accredited agent. Our sample includes 25 active concessions that were FSC-certified before 2010. As in the previous treatments, the control group consists of 194 active concessions without an FMP in 2010.

To the extent that some concessions with active permit and no approved FMP by 2010 might delay extracting timber, our definition of control group may lead to underestimating the effect of FMP approval. Indeed, in that case, the effect of FMP approval or issuance of FSC certificate are measured by comparing a treated concession that has extracted timber over the period of observation to a concession without FMP that has an active permit but did not extract timber over the same period. If timber extraction is the only source of forest cover loss in concessions with an active permit in the study area, the definitions of treatment and control groups used in this study should lead to a conservative estimate of the effect of FMP approval and FSC certification in the study area. However, it is likely that forest cover loss occurs in concession with active permit because of illegal activities and activities of communities living within or in the neighborhood of forest concessions. In this case, the definition of control group fits the theory of change and provides a fair description of the counterfactual predicted in absence of FMP.

4.2 Econometrics and identification strategy

This subsection describes the strategy used to account for the fact, compared to their peers that had not approved their FMP before 2010, the logging concessions with either an approved FMP or an FSC certificate had different characteristics known to affect deforestation. Our approach here is consistent with the previous empirical literature on the environmental impact of various policies (see for instance Blackman, 2013; Börner et al., 2016; Le Velly and Dutilly, 2016) and uses a propensity-score matching (PSM) approach to estimate the effect of FMP and FSC-certification in the Congo Basin with the least possible bias.

Using the potential-outcome framework, we consider that each logging concession has two potential outcomes $\mathbf{Y}_1$ and $\mathbf{Y}_0$, where $\mathbf{Y}_1$ is the area deforested between 2000 and 2010 for logging concessions with an approved FMP (or with FSC certification) and $\mathbf{Y}_0$ the analogous figure for concessions without an approved FMP (no FSC certification). $\mathbf{T}$ is a dummy for the concession having either an approved FMP or FSC certification. We want to estimate the average effect of having an approved FMP or FSC certification in the concessions that have them, i.e. the average treatment effect on the treated (ATT):

$$\mathbf{ATT} = \tau = \mathbb{E}\left(\mathbf{Y}_1 - \mathbf{Y}_0 \mid \mathbf{T} = 1\right) \tag{1}$$

As $\mathbf{Y}_0$ is never observed for a "treated" concession, the ATT cannot be directly estimated. Denote by $\mathbf{X}$ a set of characteristics that are known to affect deforestation and that differ across concessions that have an approved FMP or FSC certificate (which we refer to as the treatment for brevity below) and those that do not. The propensity score is $\pi\left(\mathbf{X}\right) \equiv \mathbb{P}\left(\mathbf{T} = 1 \,\middle|\, \mathbf{X}\right)$. The following assumptions, often referred to as "strong ignorability" (Rosenbaum and Rubin, 1983), imply that controlling for $\mathbf{X}$ suffices to account for the effects of the confounding factors:

$$\text{(H1)}\quad (\mathbf{Y}_1, \mathbf{Y}_0) \perp\!\!\!\perp \mathbf{T} \,\big|\, \mathbf{X} \;\text{ and (H2)}\;\; 0 < \pi(\mathbf{X}) < 1$$

H1 is often referred to as "unconfoundedness", and states that, if all confounders are included in $\mathbf{X}$, then controlling for $\mathbf{X}$ renders treatment exposure independent of the potential outcomes. Under H1, Rosenbaum and Rubin (1983) show that $(\mathbf{Y}_1, \mathbf{Y}_0) \perp\!\!\!\perp \mathbf{T} \mid \pi(\mathbf{X})$. Consequently, logging concessions with similar propensity scores would have on average similar deforestation in the absence of an approved FMP or FSC Certification and

$$\mathbb{E}\Big(\mathbf{Y}_0 \Big| \, \mathbf{T} = 1 \,,\, \pi(\mathbf{X})\Big) = \mathbb{E}\Big(\mathbf{Y}_0 \Big| \, \mathbf{T} = 0 \,,\, \pi(\mathbf{X})\Big)$$

H2 implies that, for almost all values of $\mathbf{X}$, both treated and untreated concessions have a probability of either getting an approved FMP or FSC certificate at some point. If H1 and H2 hold, then Abadie and Imbens (2016) suggest estimating the ATT τ as follows:

$$\hat{\tau} = \frac{1}{N_1} \sum_{i=1}^{N} \mathbf{T}_i \left(\mathbf{Y}_i - \frac{1}{M} \sum_{j \in \mathcal{J}_M(i)} \mathbf{Y}_j \right) .$$

Here M is a fixed number of matches per logging concession i, $\mathcal{J}_M(i)$ the set of matches for logging concession i, N the number of treated and untreated concessions, N_1 the number of concessions with the treatment and $\mathbf{T}_i$ a dummy for the concession i being treated. The matching set $\mathcal{J}_M(i)$ is defined as follows:

$$\mathcal{J}_M(i) = \Bigg\{ j = 1 \ldots N : \mathbf{T}_j = 1 - \mathbf{T}_i, \\ \left(\sum_{k:\mathbf{T}_k = 1 - \mathbf{T}_i} \mathbb{1} \left\langle |\pi(\mathbf{X}_i) - \pi(\mathbf{X}_k)| \leq |\pi(\mathbf{X}_i) - \pi(\mathbf{X}_j)| \right\rangle \right) \leq M \Bigg\}.$$

where $\mathbb{1}\langle\rangle$ is an indicator variable for the event inside the brackets holding. The set $\mathcal{J}_M(i)$ hence consists of the logging concessions that are not treated and with a propensity score similar to that of logging concession i. Overall, $\hat{\tau}$ is the average difference in the area deforested between each treated concession and the average deforestation in a set of untreated concessions with similar propensity scores. Abadie and Imbens (2016) also show that $\hat{\tau}$ produces an unbiased estimate of the ATT, while taking into account the fact that the propensity score is estimated.

4.3 Confounding factors and estimation

We consider ten key covariates known to be correlated with the likelihood of deforestation and that differ between concessions with an FMP approved or an FSC certificate and their peers without an FMP approved by 2010 (see Blackman, 2013). The selected covariates include indicators of accessibility, population pressure, biomass productivity, average steepness and elevation, which are arguably correlated to parameters that weigh into management decisions of logging companies and will indirectly influence the time needed for a concession to get their FMP approved. Four variables were used to proxy various dimensions of accessibility that are the most correlated with deforestation and are also correlated to the timing when a concession gets either its FMP approved or its FSC certificate: the distance to the road network, the distance to the nearest settlement, distance to the capital of the country and main ports, and the travel distance to a market. Settlement density is the number of settlements in a 20-kilometre radius around each settlement, and picks up population pressure. We also include the distance to a deforested area in the 1990-2000 period. Above-ground forest biomass is based on Avitabile et al. (2016) and measures the density of timber available. Elevation and slope describe the topographic environment and so suitability for logging, as steep slopes can pose problems for logging machines. Last, we control for the concession area in hectares (see Subsection S1 of the supplementary materials for details on the covariates).

4.4 Robustness checks

To produce unbiased estimates of the treatment effects, quasi-experimental approaches based on matching techniques assume that all of the relevant variables that drive deforestation and which vary between the concessions with an FMP approved (or an FSC certificate) and those without are observed and used as controls. However, this assumption is hard to test, as the real unknown variables are by definition unknown, while some known confounders (the quality of local governance, financial means of logging companies, their “readiness” to implement an FMP, and rules faced in the country they are based) are not readily available and homogeneously measured for all concessions (Panlasigui et al., 2018). If these unobservable confounders are spatially time-invariant, their effect should be seen in the difference in the area deforested in concessions with and without an FMP prior to FMP adoption, and hence between 1990 and 2000. Following this argument, we test for differences in 1990-2000 deforestation between concessions with and without FMP after matching. We furthermore consider an alternative approach that explicitly takes into account past deforestation by measuring the effect of FMP adoption on the change in deforestation over time. This change in deforestation (between 1990-2000 and 2000-2010) should in theory allow us to abstract from the effect of any unobservable factors that do not vary over time and hence should not affect the change in deforestation. This is akin to combining matching with a difference-in-difference approach. This is however not our preferred strategy, given that we do not have a true panel of logging concessions. Some logging concessions observed in 2000-2010 were not active in 1990-2000. Moreover, the deforestation data are of poorer quality between 1990 and 2000 due to the lack of satellite imagery, and the GFC dataset only covers deforestation after 2000.

4.5 Impact heterogeneity

To explore the mechanisms of change, we have randomly drawn 160,000 pixels within logging concessions from the high-resolution satellite imagery described in Section 3 (see Subsection S2 of the supplementary materials for detailed information on the pixel-sampling strategy). Then, we studied how the likelihood of forest cover loss varies across pixel randomly drawn across logging concessions and draw conclusions about spatial heterogeneity of FMP inside concessions.

To test the most-plausible pathways of the theory of change outlined above, we explore heterogeneity by the proximity of pixels to past deforestation, road networks and set-

Table 2: Predictions of the main falsifiable pathways through which FMP can affect deforestation in the short to medium run.

Variables tested in the heterogeneity analysis	Mechanism tested	Expected impact
Distance to past deforestation	Effectiveness of concession planning, especially the mapping of production series.	Less deforestation close to previous deforestation due to rotation planning, avoiding the re-exploitation of the areas previously logged.
	Effectiveness of concession monitoring, especially control of access by closing former logging roads.	Less deforestation close to previous deforestation (due to the opening of logging roads) linked to the reduction of illegal activity along former logging roads
Distance to main roads	Effectiveness of concession monitoring through control of access.	Less deforestation close to main transport networks due to reduced access from public roads.
Distance to settlements	Effectiveness of concession planning, especially the definition of areas for community and agriculture development with the promotion of sustainable activities.	Less deforestation close to settlements due to the promotion of sustainable activities and better monitoring of settlement extension.
	Effectiveness of implementation of "social contracts"	

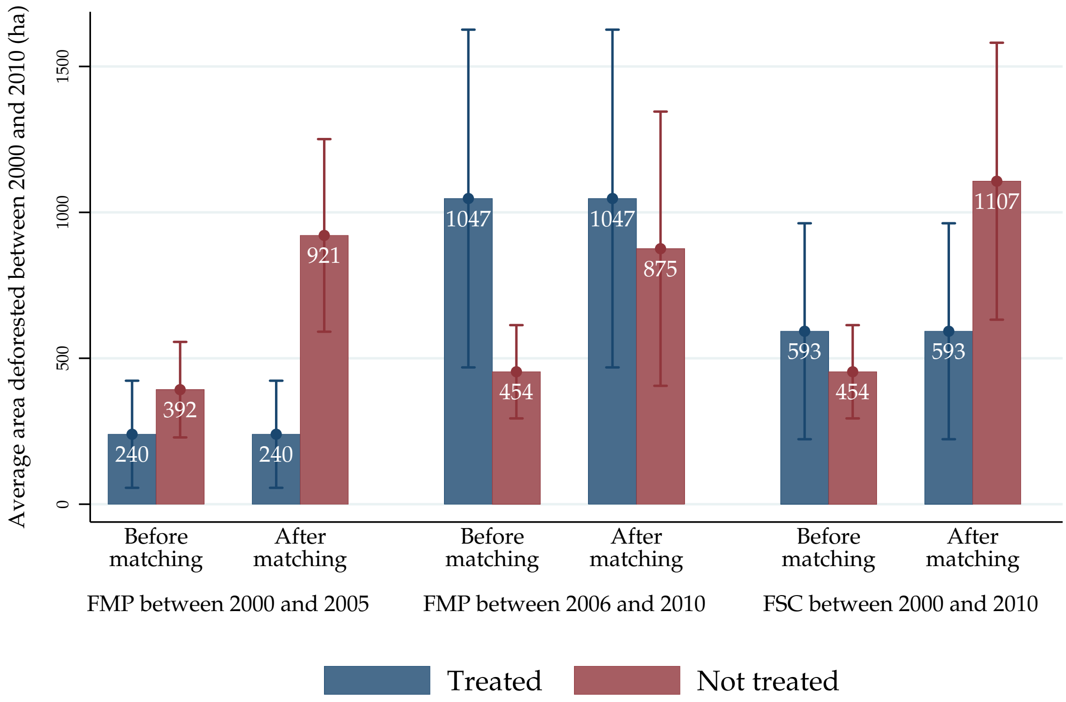
tlements (see Table 2 for a summary of the main predictions of the different plausible mechanisms). More precisely, we compare how the difference in deforestation across pixels that are close (under median distance) and far (over median distance) differs by concession FMP status. In line with the theoretical framework, we focus the heterogeneity analysis on concessions that had their FMP approved between 2000 and 2005, where the expected impact of each mechanism is more likely to be seen.

5 Results

5.1 The impact of FMP on deforestation

After matching, our estimates suggest that concessions with an FMP approved between 2000 and 2005 have less deforestation compared to otherwise-similar concessions without an FMP (see Table S3 for more details). More precisely, having an FMP

Figure 3: Difference before and after matching across treatment groups



Source: Authors' calcuations based on national high−resolution deforestation maps.

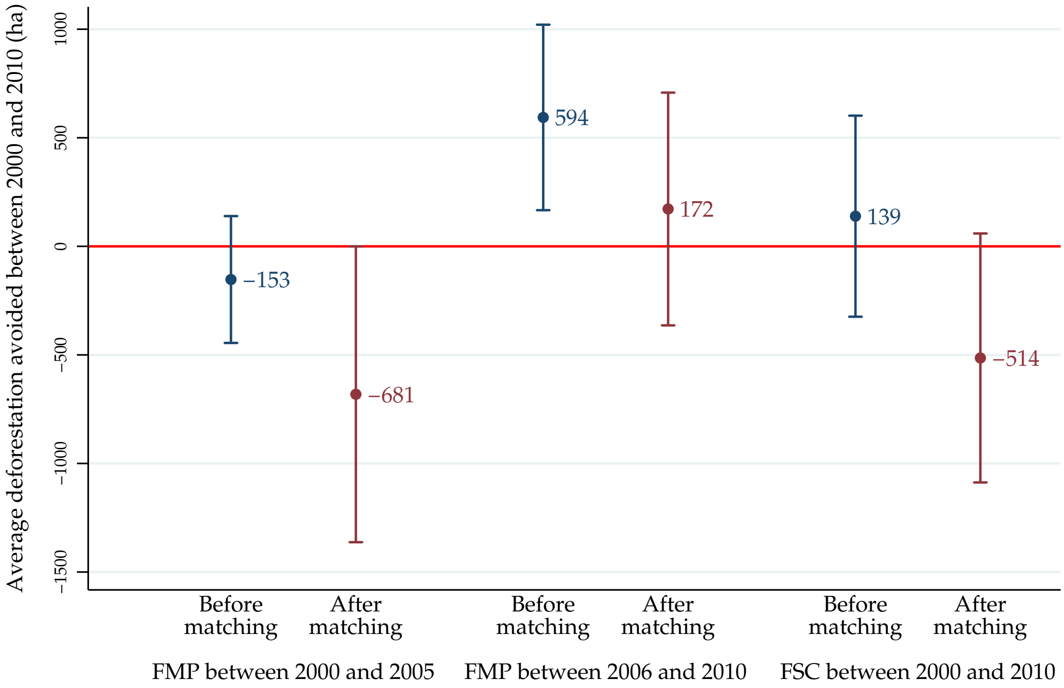
Note: The capped vertical lines represent the 95% confidence intervals around the point estimates.

approved between 2000 and 2005 is associated with average avoided deforestation of 681 ha per concession (Figure 3). Since the area deforested between 2000 and 2010 is estimated at 921 ha in control concessions, this represents a 74% fall in deforestation (Figure 3). We find similar results using estimates of the area deforested from the GFC dataset, with FMP approved between 2000 and 2005 being associated with lower deforestation of 1,005 ha for tree cover of 70% and 1,144 ha for tree cover of 30%, representing respectively drops of 74 and 75% (see Table S4).

For an FMP approved between 2006 and 2010, after matching, we find no statistically-significant impact of the FMP approval on 2000-2010 deforestation. The same result applies when the area deforested is estimated using tree-cover loss from the GFC dataset for tree cover of 70% and 30%. As such, reduced deforestation is not seen in the very short run, in line with the predictions from the theory of change.

Last, after matching, the FSC 2000-2010 treatment is also associated with a statistically-significant lower deforestation between 2000 and 2010 (at 10% p-value). Concessions

Figure 4: The impact of treatment on 2000-2010 deforestation



Source: Authors' calcuations based on national high−resolution deforestation maps.

Note: The capped vertical lines represent the 95% confidence intervals around the point estimates.

with FSC certificates, testifying that FMP have indeed been implemented, have on average an avoided deforestation estimated at 514 ha between 2000 and 2010. Compared to the average deforested area of 1,107 ha in the control concessions (all active concessions without an FMP in 2010), this represents 48% less deforestation in concessions that have received their FSC certificates between 2005 and 2010 (Figure 3 and 4). This result can be replicated using deforestation from the GFC data, with avoided deforestation in FSC 2000-2010 concessions of 699 ha for tree cover of 70% (47% less than control concessions) and 789 ha for tree cover of 30% (50% less than control concessions). We carried out complementary analyses that try to estimate the relative effectiveness of FSC certification over FMP approval (i.e. comparing FSC concessions with only FMP concessions) and also comparing FSC concessions with all no-FSC concessions (i.e concessions with approved FMP and without FSC certificate, plus active concessions without approved FMP). These analyses present several limitations that are detailed in supplementary materials (see Subsection S3). Consequently their results should be interpreted with caution. Considering these limitations and that concessions with FSC certification have had their certificates for at most five years, the complementary analyses suggest that there is no statistically significant difference of deforestation across FSC-certified concessions and their peers with approved FMP that had no FSC certificate. Therefore, the additional benefit of issuance of FSC certificate over approval of FMP seems nonexistent compared to the overall impact of implementing FMP. Likewise, we find no statistically significant difference of deforestation between concessions with FSC certificates and all their peers without FSC. This latest result is likely driven by the fact that the best match for concessions with FSC certificate are their peers with approved FMP and without FSC certificate and that, as found in the previous analysis, the relative difference of forest cover loss across these both groups is not statistically significant.

5.2 Robustness checks

The validity of all the results above rests on the assumption that the matching was successful in comparing treated and untreated concessions with similar propensity scores. Moreover, the results assume that there is no variable other than the ten covariates used as controls that drives deforestation and differs across concessions with and without an FMP approved (or an FSC certificate). In this subsection we discuss the sensitivity of our estimates to these two assumptions.

The matching was successful in balancing treated and untreated concessions with similar propensity scores. The distribution functions of the propensity scores (see Figures S2, S3 and S4) suggest that it was possible to associate each treated concession to a control concession with similar propensity score. Then, in contrast to Table S2 (characteristics of logging concessions across treatment groups before matching), Table S5 shows that the matching was successful at removing most difference in observable characteristics between treated and the untreated control concessions.

However, even after matching, control concessions cover larger tracts of land. The fact that concessions without an approved FMP still cover larger areas than their matched peer with approved FMP may suggest that the results of the matching procedure over-estimate the reduction of deforestation from the FMP. Larger concessions are indeed more likely to have larger areas deforested, even with lower deforestation rates. Yet, we find no evidence that deforestation rate is lower in concessions without approved FMP. Further analyses using deforestation rate as outcome instead of deforestation area (see Table S6 of the supplementary materials) indicate that the 2000-2010 deforestation rate is also lower in concessions with an FMP approved between 2000 and 2005 compared to concessions without FMP.

To test the sensibility of the results to unobservable heterogeneity across concessions with approved FMP (or FSC certificate) and their matched pair, we compared the difference in deforestation level between 1990 and 2000 across both groups of concessions. Although concessions with an accepted FMP between 2000 and 2005 exhibited on average less 1990-2000 deforestation than their matched peers, the difference is not statistically significant (see Table S7 for more details).

We also introduce an alternative specification to account more directly for this 1990-2000 deforestation difference, which may reveal subtle but real differences in unobservable characteristics. Following this approach, we sought to measure the effect of FMP approval on the ability of logging companies to reduce deforestation inside concessions over time. Comparing the change in deforestation between 1990-2000 and 2000-2010 across logging concessions with and without an FMP, we find that deforestation fell more in treated concessions than in control concessions without an FMP, although this difference was not statistically significant for the treatment FMP 2000-2005. We applied the same approach (see Abadie, 2005; Heckman et al., 1997, 1998, for references) for the other treatment variables, and found that deforestation between 1990-2000 and 2000-2010 fell more in concessions that had their FMP approved between 2006 and 2010 or that had received their FSC certificate before 2010 than their peers without an approved FMP (see Table S7, column *DID+PSM*, for more details).

Table 3: Likelihood of deforestation across concessions with and without a 2000-2005 FMP: Geographic heterogeneity.

	Likelihood of deforestation (in %)			ATT
	Treated	Control	Diff.	(in %)
Panel A: All pixels				
Coefficient	0.238	0.758	-0.520***	-0.270***
	(0.03)	(0.04)	(0.07)	(0.06)
Number of pixels	19,736	42,100	61,836	61,810
Panel B.1: Pixels within median distance from settlements				
Coefficient	0.310	1.248	-0.938***	-0.410***
	(0.06)	(0.08)	(0.12)	(0.11)
Number of pixels	9,365	21,555	30,920	30,904
Panel B.2: Pixels outside median distance from settlements				
Coefficient	0.174	0.243	-0.070	0.019
	(0.04)	(0.03)	(0.06)	(0.07)
Number of pixels	10,371	20,545	30,916	30,906
Panel C.1: Pixels within median distance from past deforestation				
Coefficient	0.272	1.289	-1.017***	-0.613***
	(0.05)	(0.08)	(0.12)	(0.10)
Number of pixels	10,665	20,254	30,919	30,903
Panel C.2: Pixels outside median distance from past deforestation				
Coefficient	0.198	0.265	-0.067	0.062
	(0.05)	(0.03)	(0.06)	(0.06)
Number of pixels	9,071	21,846	30,917	30,907
Panel D.1: Pixels within median distance of road network				
Coefficient	0.326	1.021	-0.695***	-0.244***
	(0.06)	(0.07)	(0.11)	(0.09)
Number of pixels	8,887	22,035	30,922	30,907
Panel D.2: Pixels outside median distance of road network				
Coefficient	0.166	0.468	-0.303***	-0.101
	(0.04)	(0.05)	(0.07)	(0.07)
Number of pixels	10,849	20,065	30,914	30,903

Note: Standard errors are in parentheses. Significance levels are denoted as follows: * p<0.10, ** p<0.05, *** p<0.01.

5.3 Impact heterogeneity

We first reproduce the main results of the paper using a sample of pixels. The results are reported in **Panel A** of Table 3 and show that pixels in concessions with approved FMP between 2000 and 2005 were less likely to lose their forest cover between 2000 and 2010 than their peers in concessions without approved FMP.

Second, spatial-heterogeneity analysis using the pixel-level database revealed that 2000-2005 FMP is associated with significantly less deforestation in areas close to settlements, close to previously-deforested areas and close to main transport network, with the measured difference being stronger for observations below the median value of these three variables (see Table 3). The ATT for all concessions on the likelihood of deforestation was smaller by 0.27 percentage points, equivalent to 53% less deforestation; the analogous figures in areas close to settlements are 0.41 (57%), in areas close to previous deforestation 0.61 (69%) and, in areas close to main transport network 0.24 (42%). Conversely, likelihood of deforestation was not statistically different across concessions with and without FMP in areas further from settlements, previously deforested areas and main transport road.

These results are in line with our expectations from our theory of change (Figure 1 and Table 2). They emphasize the effects of improvements in, first, the planning of the concessions, especially for rotation cycles and areas for community and agricultural development, second, the monitoring of concessions by closing former logging roads and monitoring the extension of settlements and agriculture areas, and, third, the monitoring of the incursion from public roads into concessions.

6 Discussion and concluding remarks

Curbing tropical deforestation is arguably a major environmental challenge. Addressing it requires the assessment of policy effectiveness and the understanding of the mechanisms underpinning their successes and failures. This paper contributes to this aim by showing that the area deforested is lower in logging concessions that have an approved FMP in the Congo Basin. More specifically, deforestation is lower in concessions that have had an FMP over a longer period. Like Panlasigui et al. (2018), this highlights the importance of the time frame: interventions aiming at increasing FMP and FSC-adoption should be evaluated over long time periods.

Evidence from analyses at the pixel level suggests that concessions with an approved FMP are less likely to over-exploit previously-logged areas. The results also suggest that concessions with an approved FMP are more likely to better control access into their perimeter and reduce deforestation around communities located within or nearby the concession. This is in line with the theory of change underpinning the implementation of forest management plans in concessions. The results confirm that spatial heterogeneity analyses are useful when evaluating policy interventions (Bruggeman et al., 2018). They add to the findings of Cerutti et al. (2017) who documented that concessions with FMP between 1998 and 2009 reduced volumes of timber harvested. Hence, reduction of the volume of timber harvested is likely another mechanism through which FMP reduced deforestation in the Congo Basin between 2000 and 2010.

Measuring the average impact of FMP on deforestation in the Congo Basin presents several challenges such as defining the right treatment groups and observation periods, and identifying a convincing strategy to isolate the average deforestation avoided attributable to FMP. Despite our attempts at addressing these challenges, the conclusions of this study rest on few key assumptions worth revisiting to outline avenues for future research.

First, the WRI and OFAC databases propose the most consistent effort to produce an updated census of logging concessions and their characteristics in the Congo Basin. However, the resulting atlas include no information documenting whether FMP are effectively implemented or the volume of timber harvested yearly in each concession. Using available information, we considered as active any concession with an exploitation permit and we identified concessions with an approved FMP, or FSC certificate, based on the date of FMP approval by the forest administrations and the date of issuance of the FSC certificate. Since approval of an FMP does not imply that the FMP is effectively implemented, we can only measure the effect of FMP approval which underestimates the effect of FMP implementation. Likewise, to the extent that some control concessions, with an exploitation permit and without approved FMP, have not started harvesting timber before 2010, our approach provides a conservative estimate of the effect of FMP approval.

Second, while the production of an FMP is mandatory across countries in the Congo Basin, logging companies chose when to draft and submit their FMP. It is then possible that concessions that had their FMP approved earlier have unobserved characteristics that led them also to deforest less. Our effort to account for this was limited by the fact that logging concessions ownership can change over time, and that information about the former management was scarce. However, taking into account previous deforestation, we found that the area deforested fell more in concessions following the approval of their FMP. Whether deforestation will also be lower in logging concessions that had their FMP approved later remains an open question. Will we continue to see lower 2005-2015 deforestation in concessions with an FMP approved between 2005 and 2010? Will there continue to be lower deforestation in concessions that had their FMP approved earlier?

Answering the above questions is a natural extension of our work and will help address the external validity of our results. This will also help inform whether the requirement to produce a forest management plan works for all concessions, and how lower deforestation varies over longer time periods. Likewise, the implementation of FMP is also expected to bring benefits other than reduced deforestation. These include, for example, conservation benefits such as reducing forest degradation and the preservation of biodiversity, and welfare improvements for the local population. Future work should therefore address other potential FMP impacts in the Congo Basin, and reveal whether lower deforestation has come at the expense of other dimensions of development and conservation.

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Declaration of interest

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S1 Covariates used in Matching

A key assumption of PSM is the selection on observables. It requires that all confounding factors influencing both reception of the treatment and the outcome variable are included in the model (Rosenbaum and Rubin, 1983). We included ten key covariates in our estimations that are known to be correlated with the likelihood of deforestation and that differ between concessions with an FMP approved or an FSC certificate and their peers without an FMP. These include indicators of accessibility, population pressure, biomass productivity and slope and elevation (Blackman, 2013). We computed the average covariates values for each concession.

Covariates of Accessibility:

- **Distance to the transport network**: calculated as the Euclidean distance to the nearest transport axis (main road, railway, navigable river) in kilometers. Distance to the transport network accounts for accessibility in two ways: on the one hand, transport infrastructure break the isolation of the forest, and, on the other hand, the lack of transport infrastructure is a brake for agricultural and forestry development.
- **Distance to the nearest settlement**: calculated as the Euclidean distance to the nearest settlement in kilometers. Spatial locations of settlements was obtained from the Forest Atlas of Congo released by WRI and OFAC. Distance to the nearest settlement accounts for accessibility by foot and intensity of forest use from people living in the settlement.
- **Distance to urban markets**: calculated as the Euclidean distance to the nearest city in kilometers. In fact, the population of cities is large and the demand for agricultural products, wood and coal from the urban population is strong. Moreover, proximity to markets increases the profitability of timber extraction and agricultural land uses.
- **Distance to the capital of the country and main ports**: calculated as the lowest

cumulative cost path to reach the nearest capital or port of export using the transport axes, which have been weighted according to their characteristics (main and secondary transport axes). This variable describes the transport constraints that weigh on some isolated regions, particularly Northern Congo, CAR or Eastern Cameroon. These logistical and financial constraints are strong for the export of timber from concessions located in these regions.

Population pressure:

- **Settlements' density**: computed using the number of settlements in a radius of twenty kilometers around each settlement. This variable describes the aggregates of settlements located close to each other, what therefore reflects a greater population pressure. In fact, the forest resources located near five settlements will, in most cases, be more intensively used than those located near a single settlement.

Several other global data on population distribution have been downloaded to analyse their consistency with local reality, such as the WorldPop and Gridded Population of the World data. However, we considered that they bring a lot of bias locally by creating artefacts in certain rural areas, in addition to have a rather low spatial resolution.

Environmental variables:

- **Distance to previous deforestation**: calculated as the Euclidean distance to the nearest deforested area in the previous period (1990-2000) in kilometers based on the map of the national forest monitoring systems of each country. Indeed, areas close to previously deforested areas have a higher probability of being deforested whether related to the expansion of rural complexes or to the use of former logging tracks.

- **Above-ground biomass in 2000**: we used the map of Avitabile et al. (2016) available at: `http://lucid.wur.nl/datasets/high-carbon-ecosystems`. This variable accounts for general differences in forest structure, forest type and forest productivity, which affect both logging and agriculture activities.

- **Elevation and Slope**: calculated using the Digital Elevation Model recorded by the Shuttle Radar Topography Mission (SRTM). These variables influence forest type, seasonal flooding, accessibility, and feasibility of logging forestry operations.

Finally, we controlled for the area of concession in hectare.

S2 Pixel level analysis of spatial heterogeneity inside concessions

To study the heterogeneity of the impact inside concession, we worked at the pixel-level and extracted a random sampling of 160.000 points in the concessions from the 2000 forest cover baseline. The pixels were selected following a stratified sampling with at least twice as many points in the control areas as in the treatment areas, in order to increase the probability of finding a good match for each point located in a concession that has adopted sustainable forest management practices. We imposed a minimum distance of 200 meters between each point to minimize spatial auto-correlation. We used each point as an observation, and extracted the value of the covariables and the outcome as a dummy variable equal to 1 if the point was deforested during the ten years period and 0 otherwise.

So, in contrast to our previous concession-level analyses where we measured avoided deforestation in hectares, the pixel-level analysis reports the likelihood that a given pixel appears deforested.

S3 Supplementary analyses of FSC impacts

Several comparisons come to mind when documenting the effects of FSC certification. The main results of the paper report the average effect of FSC certificate when FSC-certified concessions are compared to their peers that were active and had no approved FMP. However, other comparisons are possible.

First, one could measure the relative deforestation across concessions that have an FSC certificate and their peers with only an approved FMP. The results are reported in Figures S5a and S5b and suggest that the size of avoided deforestation in the concessions with FSC certificate is statistically not different from the size measured in the concessions with approved FMP and no FSC certificate. Therefore, the additional benefit of issuance of FSC certificate over approval of FMP is statistically not different from the overall impact of implementing FMP. This analysis is however based on 25 concessions with an FSC certificate issued between 2000 and 2010 against 96 concessions with only an FMP approved between 2000 and 2010. The size of the potential effect to measure and the number of concessions in both comparison groups are thus very small to produce a statistically meaningful analysis. Moreover, while the concessions with an approved FMP or an FSC certificate differ on many characteristics correlated to deforestation from their peers that have not yet approved their FMP, those characteristics are not enough to differentiate the concessions with FSC certificate from those with only an approved FMP (see Table S8). In that context, the preferred empirical strategy used in this paper – propensity score matching – is not likely to be effective at addressing the selection bias on deforestation between both groups. For these reasons, this study cannot provide a robust measure of the relative effectiveness of FSC certification over FMP approval in the Congo Basin.

Second, one may also be interested in comparing deforestation between 2000 and 2010 across concessions that have an FSC certificate and their peers with no FSC certification, whether they have an approved FMP or not. This comparison is similar to the one done by Panlasigui et al. (2018) in Cameron. The results of this comparison are reported in Figures S5a and S5b when we compare FSC and *No FSC (Only FMP + No FMP)*. The findings suggest that average deforestation in the concessions with FSC certificates is statistically not different from that measured in their closest peers with no FSC certificate. This result is consistent with the fact that the closest peers of concessions with an FSC certificate are those that had an approved FMP and no FSC certificate. From the previous analysis we know that the difference of deforestation between both groups is small and not statistically significant. This finding suggests that comparing concessions with FSC to their peers without FSC certificate is likely to overlook the benefit of having an FSC certificate over managing a concession with no FMP.

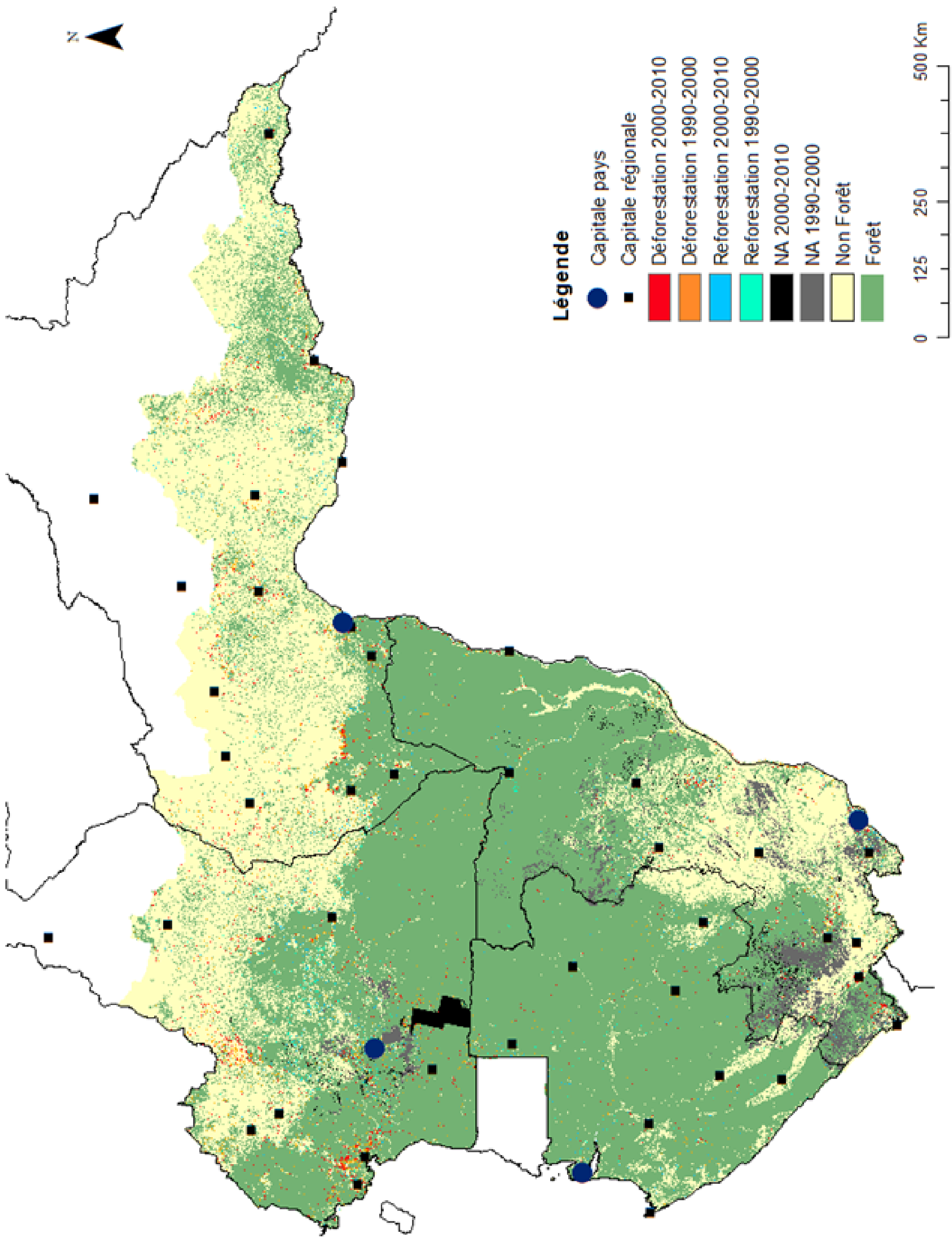
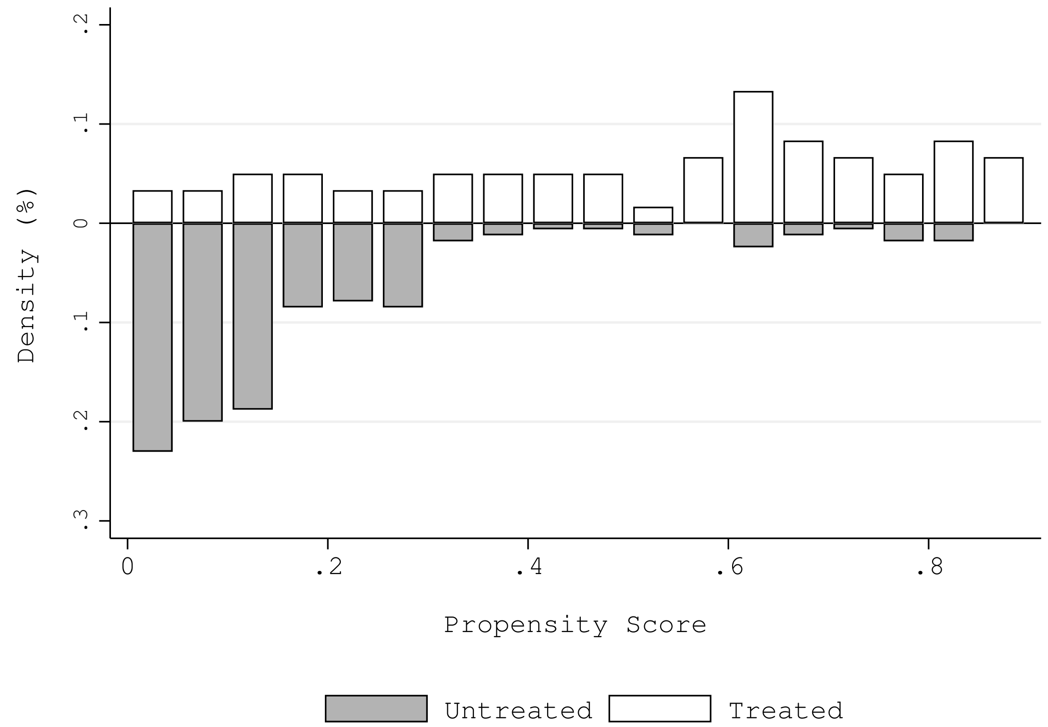
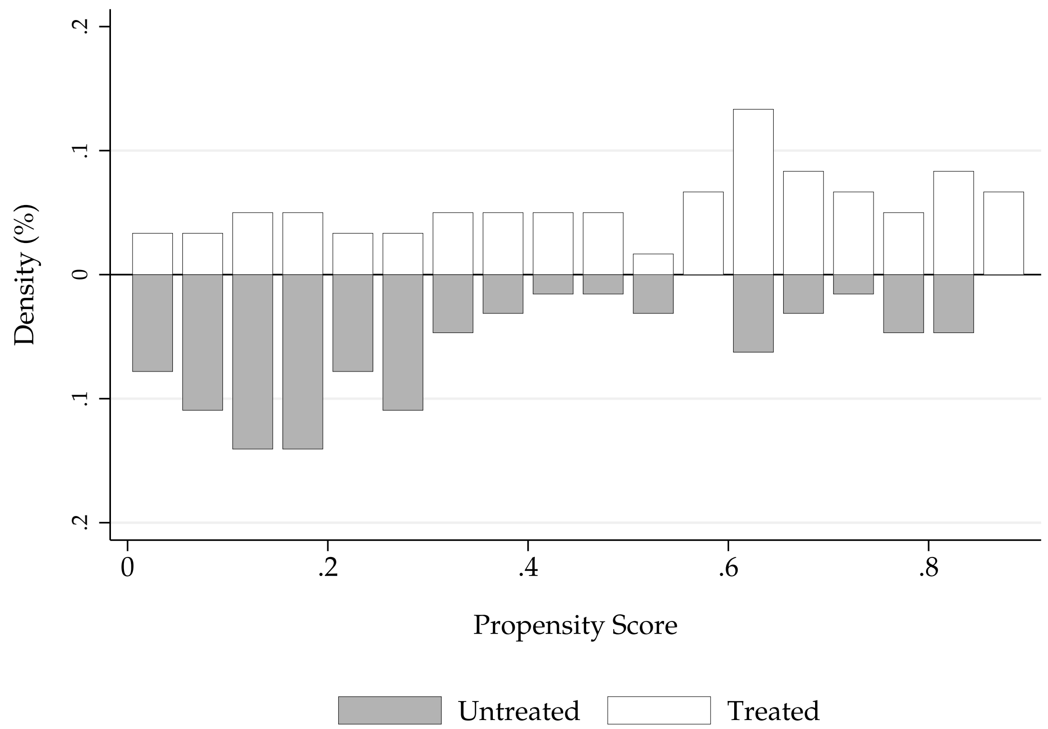


Figure S1: Forest area and change in the study area between 1990-2000 and 2000-2010

Figure S2: Distribution of propensity scores for active concessions with and without an FMP approved between 2000 and 2005.

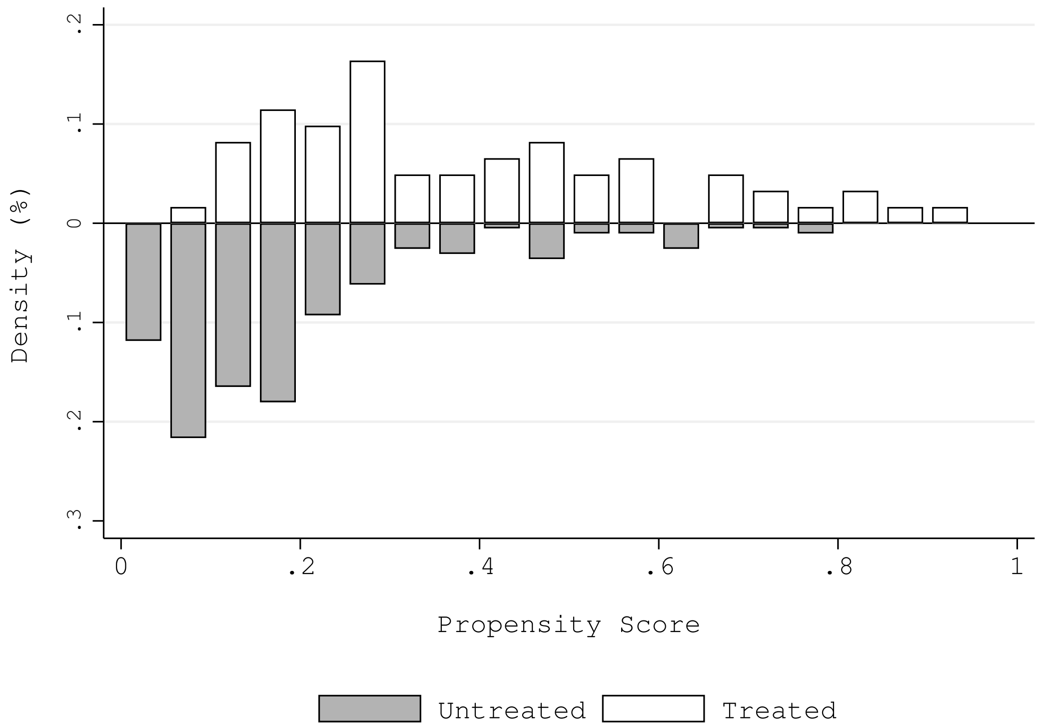


(a) Before matching

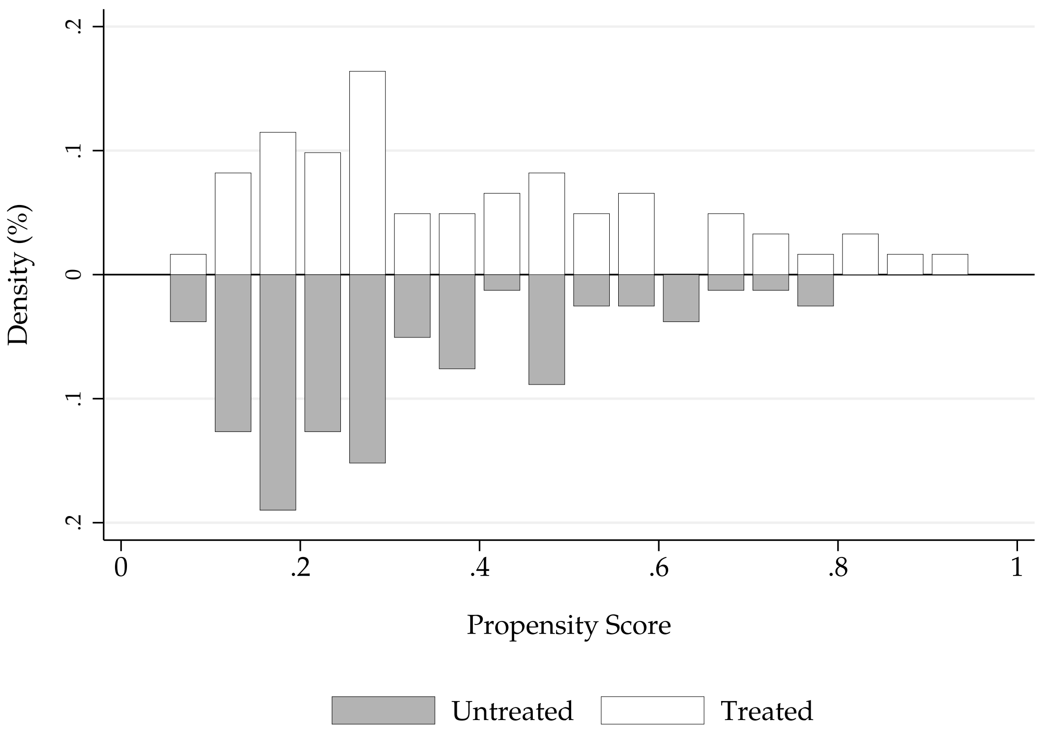


(b) After matching

Figure S3: Distribution of propensity scores for active concessions with and without an FMP approved between 2006 and 2010.

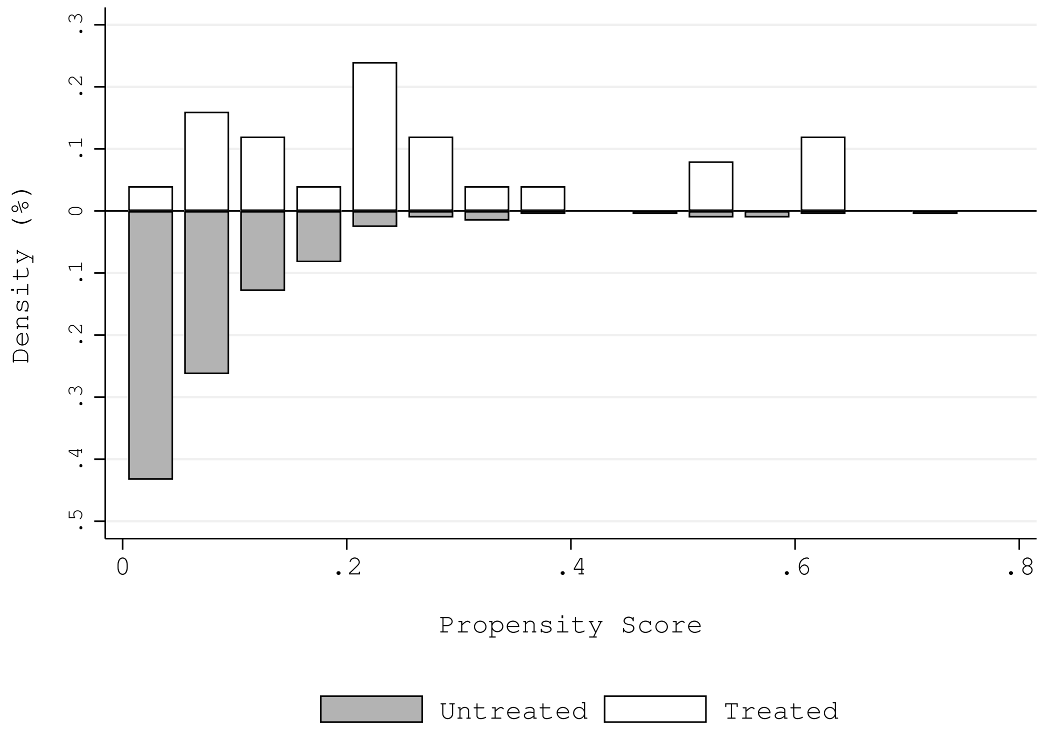


(a) Before matching

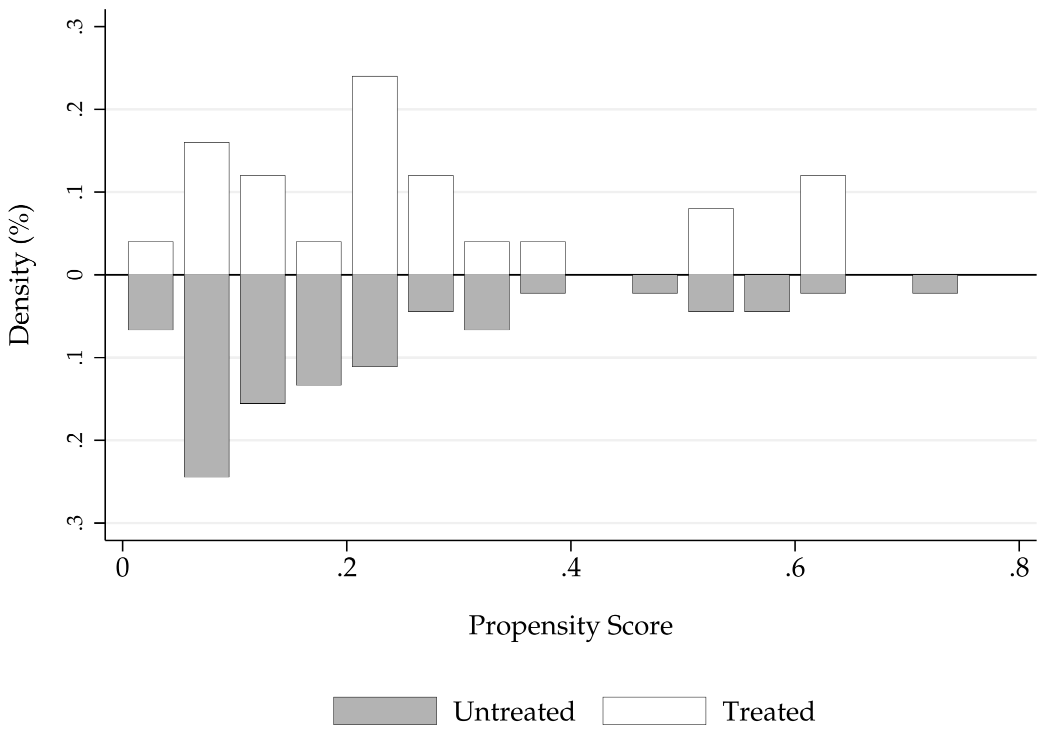


(b) After matching

Figure S4: Distribution of propensity scores for active concessions with and without an FSC certificate issued between 2000 and 2010.

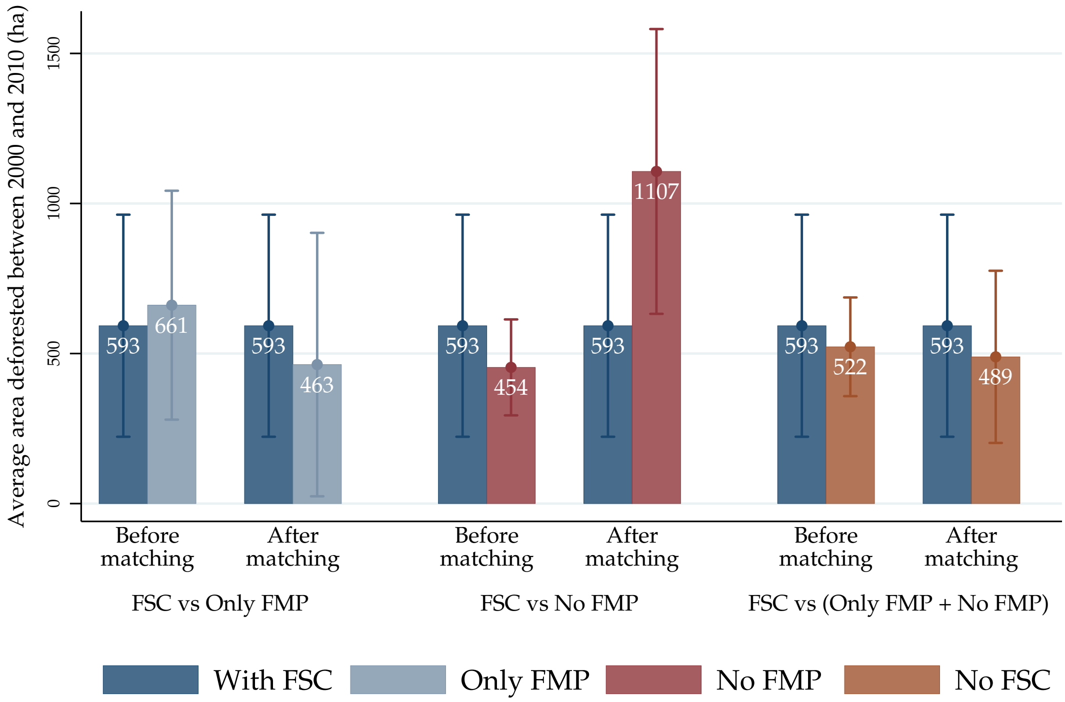


(a) Before matching



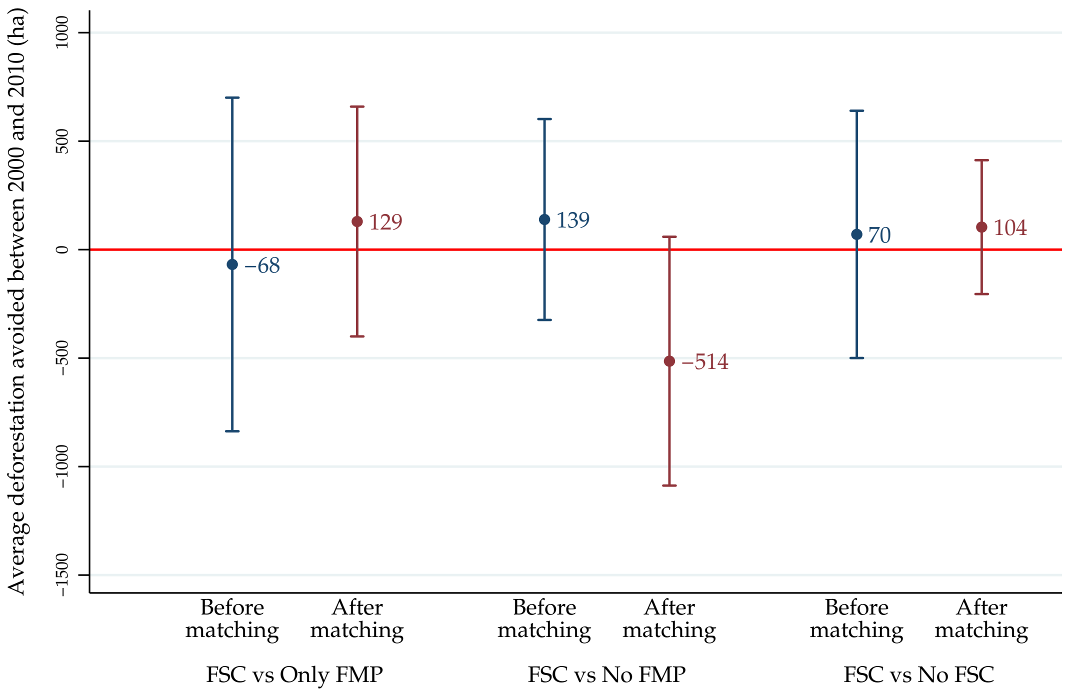
(b) After matching

Figure S5: Comparing the relative impact of FSC certificate over approval of FMP on 2000-2010 deforestation



Source: Authors' calcuations based on national high−resolution deforestation maps.

(a) Average deforestation across groups



Source: Authors' calcuations based on national high−resolution deforestation maps.

(b) Relative difference of deforestation across groups

Table S1: Descriptive statistics of key variables

	Obs	Min	Mean	s.d.	Max
Forest loss between 2000 and 2010 (ha)					
- *from national maps*	315	0	528.0	1387.5	12808.5
- *from GFC with 30% tree cover*	314	0.36	594.2	1255.5	7879.8
- *from GFC with 70% tree cover*	314	0.36	524.9	1119.6	6710.7
Forest loss between 1990 and 2000 (ha)	315	0	546.0	1611.5	18078.4
Number of years of activity	315	2	10.8	6.99	42
Date when FMP was accepted					
- *No FMP*	315	0	0.54	0.50	1
- *2000-2005*	315	0	0.19	0.39	1
- *2006-2010*	315	0	0.19	0.40	1
- *2010-2016*	315	0	0.079	0.27	1
Distance to nearest road (km)	315	1.28	19.0	15.5	87.9
Distance to market (km)	315	12.6	96.4	49.2	252.1
Distance to capital (km)	315	78.2	465.9	201.1	1001.9
Distance to previous deforestation	315	0.68	5.51	4.29	29.4
Distance to nearest settlement (km)	315	18.5	111.9	71.4	553.6
Settlement density (nb villages within 20 km)	315	0	0.011	0.010	0.067
Above-ground forest biomass (Mg/ha)	315	22.8	380.9	90.0	516.1
Elevation (m)	315	23.7	433.0	210.6	756.0
Slope (%)	315	0.28	1.76	1.19	7.19
Area of concession (1000 ha)	315	1.50	98.1	142.7	1226.7

Note: The table presents descriptive statistics of the main variables considered in this study.

Table S2: Characteristics of logging concessions across treatment groups before matching.

Variables	FMP 2000-05			FMP 2006-10			FSC 2000-10		
	Treated	Control	diff.	Treated	Control	diff.	Treated	Control	diff.
Forest loss over 2000-10 (ha)									
- *from national maps*	239.62	392.46	-152.84	1047.47	453.79	593.67***	592.63	453.79	138.83
	(91.69)	(82.88)	(148.25)	(289.33)	(81.04)	(216.88)	(179.26)	(81.04)	(234.89)
- *from GFC with 30% tree cover*	377.89	450.79	-72.90	1034.87	522.23	512.65***	785.28	522.23	263.05
	(91.69)	(85.61)	(152.13)	(231.82)	(82.34)	(195.83)	(259.68)	(82.34)	(247.02)
- *from GFC with 70% tree cover*	353.14	391.76	-38.62	913.32	455.49	457.83***	745.19	455.49	289.70
	(87.51)	(76.46)	(137.13)	(205.34)	(73.29)	(173.93)	(251.21)	(73.29)	(222.60)
Forest loss between 1990 and 2000 (ha)	425.57	251.48	174.08	1359.25	327.56	1031.69***	868.07	327.56	540.51**
	(150.56)	(55.85)	(129.54)	(372.68)	(68.65)	(241.50)	(281.73)	(68.65)	(215.93)
Distance to nearest road (km)	26.94	15.63	11.31***	22.37	15.44	6.93***	25.95	15.44	10.51***
	(2.01)	(1.11)	(2.21)	(2.21)	(0.98)	(2.15)	(3.33)	(0.98)	(2.99)
Distance to market (km)	121.34	82.15	39.18***	115.35	82.78	32.57***	99.74	82.78	16.97**
	(6.50)	(3.20)	(6.59)	(7.46)	(2.88)	(6.62)	(7.51)	(2.88)	(8.47)
Distance to capital (km)	525.30	438.41	86.89***	477.98	443.70	34.27	557.53	443.70	113.82***
	(26.80)	(14.84)	(29.43)	(27.40)	(13.76)	(28.95)	(39.01)	(13.76)	(40.81)
Distance to previous deforestation	5.05	5.64	-0.59	5.25	5.73	-0.47	5.34	5.73	-0.38
	(0.55)	(0.32)	(0.63)	(0.60)	(0.30)	(0.63)	(0.51)	(0.30)	(0.85)
Distance to nearest settlement (km)	131.60	100.50	31.11***	123.55	102.17	21.38**	133.75	102.17	31.58**
	(8.26)	(5.87)	(10.94)	(7.99)	(5.36)	(10.56)	(11.47)	(5.36)	(15.50)
Settlement density (nb villages within 20 km)	0.01	0.01	-0.00*	0.01	0.01	-0.00*	0.01	0.01	-0.01**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Above-ground forest biomass (Mg/ha)	434.17	353.51	80.66***	406.74	356.34	50.39***	421.49	356.34	65.15***
	(7.24)	(7.65)	(13.42)	(7.96)	(6.92)	(13.14)	(8.12)	(6.92)	(19.54)
Elevation (m)	545.29	361.58	183.71***	491.06	380.06	111.01***	472.80	380.06	92.74**
	(22.62)	(16.92)	(31.22)	(22.08)	(15.35)	(30.06)	(37.12)	(15.35)	(44.82)
Slope (%)	1.53	1.90	-0.37*	1.83	1.82	0.01	1.57	1.82	-0.25
	(0.11)	(0.11)	(0.19)	(0.13)	(0.09)	(0.18)	(0.23)	(0.09)	(0.27)
Area of concession (1000 ha)	99.12	63.78	35.33**	162.20	77.61	84.59***	195.98	77.61	118.37***
	(12.58)	(9.60)	(17.64)	(24.56)	(9.38)	(21.64)	(51.80)	(9.38)	(31.93)
Number of concessions	60	165	225	61	194	255	25	194	219

Note: Standard errors are in parentheses. Significance levels are reported for t-tests of the equality of the means across treatment groups. They are denoted as follows: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table S3: Deforestation across concessions upon acceptance of FMP and issuance of FSC certificate.

	Deforestation in concessions			ATT
	Treated	Control	Diff.	(in ha)
Treatment: FMP approved between 2000 and 2005				
Coefficient	239.62	392.46	-152.84	-681.40**
	(91.7)	(82.9)	(148.3)	(347.6)
Number of concessions	60	165	225	225
Treatment: FMP approved between 2006 and 2010				
Coefficient	1047.47	453.79	593.67***	171.97
	(289.3)	(81.0)	(216.9)	(273.5)
Number of concessions	61	194	255	255
Treatment: FSC certificate issued between 2000 and 2010				
Coefficient	592.63	453.79	138.83	-514.11*
	(179.3)	(81.0)	(234.9)	(292.5)
Number of concessions	25	194	219	219

Note: The table reports estimates of average deforestation over the period 2000-2010 across treatment groups as described in Section 4. Standard errors are in parentheses. Significance levels are denoted as follows: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table S4: Deforestation across concessions upon acceptance of FMP and issuance of FSC certificate (using data from GFC).

	Area with at least 30% tree cover				Area with at least 70% tree cover			
	Deforestation in concessions			ATT	Deforestation in concessions			ATT
	Treated	Control	Diff.	(in ha)	Treated	Control	Diff.	(in ha)
Treatment: FMP approved between 2000 and 2005								
Coefficient	377.89	450.79	-72.90	-1143.54***	353.14	391.76	-38.62	-1004.96***
	(91.7)	(85.6)	(152.1)	(412.2)	(87.5)	(76.5)	(137.1)	(374.7)
Number of concessions	60	164	224	224	60	164	224	224
Treatment: FMP approved between 2006 and 2010								
Coefficient	1034.87	522.23	512.65***	126.86	913.32	455.49	457.83***	67.29
	(231.8)	(82.3)	(195.8)	(204.8)	(205.3)	(73.3)	(173.9)	(193.8)
Number of concessions	61	193	254	254	61	193	254	254
Treatment: FSC certificate issued between 2000 and 2010								
Coefficient	785.28	522.23	263.05	-789.09***	745.19	455.49	289.70	-698.68***
	(259.7)	(82.3)	(247.0)	(265.3)	(251.2)	(73.3)	(222.6)	(237.6)
Number of concessions	25	193	218	218	25	193	218	218

Note: The table reports estimates of average tree cover loss over the period 2000-2010 across treatment groups as described in Section 4. Mesures of tree cover loss is derived from the Global Forest Change (GFC) dataset (1.0) (Hansen et al., 2013). Standard errors are in parentheses. Significance levels are denoted as follows: * p<0.10, ** p<0.05, *** p<0.01.

Table S5: Characteristics of logging concessions across treatment groups after matching.

Variables	FMP 2000-05			FMP 2006-10			FSC 2000-10		
	Treated	Control	diff.	Treated	Control	diff.	Treated	Control	diff.
Distance to nearest road (km)	26.94	23.97	2.97	22.37	22.17	0.21	25.95	23.98	1.98
	(2.17)	(2.17)	(3.07)	(2.03)	(2.03)	(2.87)	(2.96)	(2.96)	(4.18)
Distance to market (km)	121.34	124.13	-2.80	115.35	105.20	10.15	99.74	110.63	-10.89
	(6.20)	(6.20)	(8.77)	(6.06)	(6.06)	(8.57)	(6.64)	(6.64)	(9.39)
Distance to capital (km)	525.30	451.12	74.18**	477.98	448.42	29.56	557.53	523.33	34.19
	(22.87)	(22.87)	(32.35)	(22.25)	(22.25)	(31.46)	(29.68)	(29.68)	(41.98)
Distance to previous deforestation	5.05	4.69	0.36	5.25	5.55	-0.29	5.34	5.26	0.08
	(0.46)	(0.46)	(0.65)	(0.47)	(0.47)	(0.67)	(0.46)	(0.46)	(0.65)
Distance to nearest settlement (km)	131.60	117.48	14.12	123.55	135.36	-11.80	133.75	130.51	3.24
	(8.38)	(8.38)	(11.85)	(8.83)	(8.83)	(12.48)	(10.09)	(10.09)	(14.27)
Settlement density (nb villages within 20 km)	0.01	0.01	-0.00	0.01	0.01	0.00	0.01	0.01	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Above-ground forest biomass (Mg/ha)	434.17	422.94	11.23	406.74	409.68	-2.94	421.49	421.09	0.40
	(7.20)	(7.20)	(10.18)	(6.91)	(6.91)	(9.78)	(7.62)	(7.62)	(10.78)
Elevation (m)	545.29	528.14	17.15	491.06	492.48	-1.42	472.80	468.55	4.25
	(20.94)	(20.94)	(29.62)	(20.44)	(20.44)	(28.91)	(30.59)	(30.59)	(43.26)
Slope (%)	1.53	1.43	0.09	1.83	2.04	-0.22	1.57	1.55	0.02
	(0.11)	(0.11)	(0.16)	(0.16)	(0.16)	(0.23)	(0.18)	(0.18)	(0.26)
Area of concession (1000 ha)	99.12	187.13	-88.02***	162.20	157.64	4.56	195.98	210.30	-14.32
	(20.56)	(20.56)	(29.08)	(23.42)	(23.42)	(33.12)	(40.47)	(40.47)	(57.23)
Number of concessions	124	124	124	140	140	140	70	70	70

Note: The table reports differences between treated and control groups after matching. Standard errors are in parentheses. They do not account for the fact that the propensity scores are estimated and should be taken with caution. Significance levels are reported for t-tests of the equality of the means across treatment groups. They are denoted as follows: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table S6: Deforestation rate across concessions upon acceptance of FMP and issuance of FSC certificate.

	Deforestation rate (in %)			ATT
	Treated	Control	Diff.	(in %)
Treatment: FMP approved between 2000 and 2005				
Coefficient	0.141	0.506	-0.365**	-0.217**
	(0.03)	(0.09)	(0.14)	(0.09)
Number of concessions	60	165	225	225
Treatment: FMP approved between 2006 and 2010				
Coefficient	0.536	0.520	0.016	0.101
	(0.11)	(0.08)	(0.15)	(0.14)
Number of concessions	61	194	255	255
Treatment: FSC certificate issued between 2000 and 2010				
Coefficient	0.254	0.520	-0.266	0.070
	(0.04)	(0.08)	(0.22)	(0.07)
Number of concessions	25	194	219	219

Note: The table reports estimates of average deforestation rates over the period 2000-2010 across treatment groups. Standard errors are in parentheses. Significance levels are denoted as follows: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table S7: Deforestation across concessions upon acceptance of FMP and issuance of FSC certificate (using past levels of deforestation).

	Deforestation 1990-2000			ATT	
	Treated	Control	Diff.	PSM	DID+PSM
Treatment: FMP approved between 2000 and 2005					
Coefficient	425.57	251.48	174.08	-474.36	-207.04
	(150.6)	(55.9)	(129.5)	(365.5)	(167.8)
Number of concessions	60	165	225	225	225
Treatment: FMP approved between 2006 and 2010					
Coefficient	1359.25	327.56	1031.69***	671.98**	-500.00***
	(372.7)	(68.6)	(241.5)	(304.9)	(166.9)
Number of concessions	61	194	255	255	255
Treatment: FSC certificate issued between 2000 and 2010					
Coefficient	868.07	327.56	540.51**	-122.06	-392.06**
	(281.7)	(68.6)	(215.9)	(318.4)	(175.3)
Number of concessions	25	194	219	219	219

Note: The table reports estimates of the average effects of various treatments on deforestation in each treated group. The first column reports the average level of deforestation in the treated concessions between 1990 and 2000. The second column reports the average level of deforestation between 1990 and 2000 in corresponding control groups. The third column reports the simple difference of average deforestation between 1990 and 2000 across treated and control groups. The fourth column (ATT-PSM) reports the average difference of deforestation between 1990 and 2000 across treated and corresponding controls after matching with their most similar peers. The fifth column compares the variation over time of deforestation level between 1990-2000 and 2000-2010 (i.e. deforestation 2000-2010 - deforestation 1990-2000) in treated group to the variation observed in the concession that resemble them the most after matching. This approach combines a difference-in-difference (DID) approach and a propensity score matching (PSM) approach (see Abadie, 2005; Heckman et al., 1997, 1998, for references). Standard errors are in parentheses. Significance levels are denoted as follows: * p<0.10, ** p<0.05, *** p<0.01.

Table S8: Characteristics of concessions with FSC and with only FMP before matching.

Variables	FMP 2000-2010 vs. No FMP			FSC 2000-2010 vs. No FMP			FSC 2000-2010 vs. FMP 2000-2010		
	with FMP	No FMP	diff.	With FSC	No FMP	diff.	With FSC	Only FMP	diff.
Forest loss over 2000-10 (ha)									
- *from national maps*	646.88	453.79	193.09	592.63	453.79	138.83	592.63	661.01	-68.38
	(156.56)	(81.04)	(160.62)	(179.26)	(81.04)	(234.89)	(179.26)	(192.09)	(388.25)
- *from GFC with 30% tree cover*	709.09	522.23	186.87	785.28	522.23	263.05	785.28	689.25	96.02
	(128.43)	(82.34)	(145.43)	(259.68)	(82.34)	(247.02)	(259.68)	(147.67)	(318.42)
- *from GFC with 70% tree cover*	635.54	455.49	180.05	745.19	455.49	289.70	745.19	606.99	138.20
	(114.67)	(73.29)	(129.64)	(251.21)	(73.29)	(222.60)	(251.21)	(129.39)	(284.13)
Forest loss between 1990 and 2000 (ha)	896.27	327.56	568.70***	868.07	327.56	540.51**	868.07	903.61	-35.54
	(205.80)	(68.65)	(184.20)	(281.73)	(68.65)	(215.93)	(281.73)	(249.41)	(510.42)
Distance to nearest road (km)	24.64	15.44	9.20***	25.95	15.44	10.51***	25.95	24.30	1.66
	(1.50)	(0.98)	(1.72)	(3.33)	(0.98)	(2.99)	(3.33)	(1.69)	(3.73)
Distance to market (km)	118.32	82.78	35.54***	99.74	82.78	16.97**	99.74	123.16	-23.41*
	(4.94)	(2.88)	(5.34)	(7.51)	(2.88)	(8.47)	(7.51)	(5.82)	(12.05)
Distance to capital (km)	501.44	443.70	57.74**	557.53	443.70	113.82***	557.53	486.84	70.69
	(19.21)	(13.76)	(23.10)	(39.01)	(13.76)	(40.81)	(39.01)	(21.83)	(47.20)
Distance to previous deforestation	5.15	5.73	-0.57	5.34	5.73	-0.38	5.34	5.10	0.24
	(0.41)	(0.30)	(0.50)	(0.51)	(0.30)	(0.85)	(0.51)	(0.50)	(1.01)
Distance to nearest settlement (km)	127.54	102.17	25.37***	133.75	102.17	31.58**	133.75	125.93	7.82
	(5.73)	(5.36)	(8.16)	(11.47)	(5.36)	(15.50)	(11.47)	(6.60)	(14.21)
Settlement density (nb villages within 20 km)	0.01	0.01	-0.00***	0.01	0.01	-0.01**	0.01	0.01	-0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Above-ground forest biomass (Mg/ha)	420.34	356.34	64.00***	421.49	356.34	65.15***	421.49	420.04	1.45
	(5.51)	(6.92)	(9.79)	(8.12)	(6.92)	(19.54)	(8.12)	(6.63)	(13.66)
Elevation (m)	517.95	380.06	137.90***	472.80	380.06	92.74**	472.80	529.71	-56.91
	(15.93)	(15.35)	(23.16)	(37.12)	(15.35)	(44.82)	(37.12)	(17.50)	(39.16)
Slope (%)	1.68	1.82	-0.14	1.57	1.82	-0.25	1.57	1.71	-0.14
	(0.09)	(0.09)	(0.14)	(0.23)	(0.09)	(0.27)	(0.23)	(0.09)	(0.22)
Area of concession (1000 ha)	130.92	77.61	53.31***	195.98	77.61	118.37***	195.98	113.98	82.01**
	(14.10)	(9.38)	(16.28)	(51.80)	(9.38)	(31.93)	(51.80)	(11.21)	(34.17)
Number of concessions	121	194	315	25	194	219	25	96	121

Note: Standard errors are in parentheses. Significance levels are reported for t-tests of the equality of the means across treatment groups. They are denoted as follows: * p<0.10, ** p<0.05, *** p<0.01.