Do Forest-Management Plans and FSC certification reduce deforestation in the Congo Basin?

Highlights

- The adoption of sustainable forest-management practices that are FSC-certified or with an accepted forest-management plan is associated with less deforestation in the Congo Basin
- This lower deforestation takes at least five years to come about in concessions with a forest-management plan
- The fall in deforestation is more pronounced around communities located within or nearby to logging concessions and close to sites of previous deforestation.

Abstract: To allow for the production of timber while preserving conservation values, forestry regulations in the Congo Basin have made Forest Management Plans (FMPs) 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 FMPs on deforestation in this region. We apply quasi-experimental and difference-in-difference approaches to evaluate the change in deforestation in concessions that implemented an FMP. We find that deforestation fell by 74% between 2000 and 2010 in concessions with an FMP. Building on a theory of change, further analyses revealed that this lower deforestation takes at least five years to come about, and is highest around communities located in and nearby logging concessions and in areas close to previous deforestation. These findings suggest that FMPs reduce deforestation by allowing concessions to rotate cycles of timber extraction, thereby avoiding the (over-) exploitation 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 slash and burn agriculture, hunting and the illegal harvest of timber or fuelwood.

Keyword: forest management plan; FSC certification; deforestation; quasi-experimental matching; causal mechanisms; Congo basin.

1 Introduction

About 400 million hectares of natural tropical forest are devoted to timber production (Blaser, 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. National forestry regulations have made Forest Management Plans (FMPs) mandatory in logging concessions to ensure their sustainable exploitation. The FMP must ensure sustainable forest management, that is 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).

For this reason, and because of the extent of forest areas covered, FMPs are often considered as a major contribution to tropical forest conservation worldwide, and have been supported by international organizations and NGOs (Clark et al., 2009; Lambin et al., 2014). However, there is relatively scant empirical work on their effect on deforestation in logging concessions. Cerutti et al. (2017) showed that FMPs 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. On the contrary, Brandt et al. (2016) found that FMP concessions 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 FMPs in the Congo (Brandt et al., 2014, 2016). 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 FMPs affect deforestation.

While there is a paucity of work on the effects of FMPs, relatively more attention has been given to Forest Steward Council (FSC) certification: this is a voluntary market-based approach to enhance sustainable forest management. As halting tropical deforestation remains a central FSC objective, within a wide range of issues covered by FSC standards, a number of empirical contributions have looked at the impact of FSC certification on deforestation. The results here are also mixed and context-dependent. Some work on Cameroon (Panlasigui et al. 2018), Mexico (Blackman et al. 2018), and Brazil, Gabon and Indonesia (Rana and Sills 2017) has shown that FSC certification reduced deforestation in most certified logging concessions, but that the estimated effects were rarely statistically different from zero and varied over time, thus providing inconclusive evidence of the deforestation impact of FSC. Miteva et al. (2015) showed that FSC certification in Indonesia reduced deforestation and improved household welfare. In Chile, Heilmayr and Lambin (2016) compared the deforestation impacts of three different non-State market-driven governance regimes, among which FSC certification: they showed that FSC certification effectively reduced deforestation, and was more effective than the other measures tested, which were more industry-friendly.

Overall, the impact of the adoption of sustainable forest-management practices on deforestation in the Congo Basin remains an active research area. The results from similar policy interventions in Asia and South America suggest that the results are context-dependent and can therefore not be directly transposed. As reducing deforestation in low-income countries is arguably one of the most cost-effective ways of reducing global CO2 emissions (Stern, 2006, and Barker et al., 2007), this paper aims to evaluate the change in forest cover following the implementation of an FMP or FSC certification in the Congo Basin, and to establish the underlying mechanisms explaining whether and how these work (Baylis et al., 2016; Miteva et al., 2012).

To provide an empirical estimate of the impact of FMPs in the Congo Basin, we use original high-resolution maps of changes in forest cover in Cameroon, Congo, Gabon and the Central African Republic (CAR) over the 1990-2000 and 2000-2010 periods. The geographic area does not include forest-cover changes in the Democratic Republic of Congo, where FMPs 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. As the selection into FMP adoption is not random, we use quasi-experimental methods whereby the logging concessions that adopted FMP are compared to logging concessions that did not adopt an FMP but had otherwise similar observable characteristics that are known to affect deforestation.

This approach will likely produce unbiased estimates of the effect of FMPs in the study areas for at least two reasons. First, since the 1990’s, Cameroon, Congo, CAR and Gabon have all implemented reforms aimed at encouraging logging companies to adopt FMPs (Karsenty, 2006). FMP were then gradually implemented in the 2000s, and by 2010 almost 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. Given the staggered rollout of reforms promoting FMP adoption in the region, it is likely that we will find otherwise-similar concessions with and without FMPs, which is a key requirement for unbiased quasi-experimental analysis. Second, even though national policies aiming to increase FMP adoption have been discussed since the 1990s, the first logging concessions with FMPs 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 in data from 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 by considering the Congo Basin. As we cover a larger sample of logging concessions, we avoid the limitations of analyses based on smaller samples.

The remainder of the paper is organized as follows. In Section 2 we present background information on forest-management plans 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 FMPs on deforestation. Section 5 presents the main results and their robustness and limitations, and explores the channels underlying the link between FMPs and deforestation. Last, Section 6 discusses the implications of our work and offers 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 long periods (up to 100 years) under concession regimes, providing long-term resource-extraction rights in exchange for a stream of revenues (Agrawal et al., 2008). In this context FMPs are a tool for sustainable forest management, combining timber production, local development and conservation values in the Congo Basin.

2.1 Forest-Management Plans in the Congo Basin

FMPs in a concession involve a range of environmental and social issues. They are based on forest inventories describing the distribution of trees species and their characteristics. Based on ecological and social studies (e.g., on fauna and the forest uses of local communities), these inventories allow us to divide each concession into "management series" areas according to the use of forest resources. Among these, the "production", "conservation" and "community management" series respectively refer to: wood exploitation; the preservation of biodiversity, seed trees and the most vulnerable areas (with buffer zones on steep slopes, riversides etc.); and last local-community development. These community-management series are located around settlements and agricultural areas, and aim to ensure the coexistence of different forest uses in order to guarantee the land rights of local populations and encourage local communities to carry out sustainable natural-resource management, in particular regarding hunting and agriculture (ATIBT, 2007; Nkeoua, 2003). The production series are divided into "annual cutting areas (ACA)", 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 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). In addition, FMPs recommend reduced-impact logging (RIL) practices and facilitate checks on operating activities by regulators (Cerutti et al., 2008; Ezzine de Blas and Ruiz Pérez, 2008; Karsenty et al., 2008; Putz et al., 2008a).

For local development, FMPs require that concessions adhere to "social contracts", redistributing part of the benefits to the local population, either through specific forest taxation or the direct funding of local infrastructure (for example, companies often build wood-processing facilities, such as sawmills, that employ local workers; ATIBT, 2007).

In all of the Congo Basin countries except the CAR,[1] the FMP is established 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. Moreover, FMPs may not deliver the expected outcomes. First, logging concessions are responsible for the drafting of the FMP, which will thus 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 officially-approved FMP exists is neither a quality guarantee nor an indication of its implementation on the ground (Karsenty et al., 2017).

2.2 FSC certification: an additional guarantee of sustainable forest management

To show their commitment toward sustainable forest management, logging companies with an accepted FMP can apply to be certified by the Forest Stewardship Council (FSC). This is a voluntary, market-based approach to enhancing sustainable forest management. Concessions with FSC

[1] 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 FMPs (the PARPAF project financed by the AFD).

certification commit to comply to FSC standards, which aim to promote "*environmentally appropriate, socially beneficial and economically viable management of the world's forests*" (FSC, 2018). 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, concessions 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 certification for five years, during which they carry out annual concession inspections to ensure their continued compliance (FSC, 2018).

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

2.3 Theory of change

>>>> HERE Figure 1. Theory of change <<<<

Figure 1 summarizes the theory of change through which the adoption of sustainable forest-management practices via FMP and FSC is supposed to reduce deforestation in logging concessions. FMP and FSC can have a variety of impacts, including social and economic benefits and reduced forest degradation, which are likely correlated with deforestation. However, the exact measurement of them mis beyond the scope of our work here, which will focus only on deforestation. Our theoretical framework is then articulated around five main causal pathways relating forest management to deforestation: (i) concession planning; (ii) monitoring of the concession for settlement expansion, agriculture expansion and illegal activities; (iii) planning of the logging-track network, log landings and skid trails; (iv) improvements in forestry-management practices and logging techniques; and (v) improved livelihoods for local communities (Cerutti et al., 2017; Durrieu de Madron et al., 2011; Ezzine de Blas and Ruiz Pérez, 2008; Pearson et al., 2014; Putz et al., 2008a, 2008b).

The FMP first allows logging firms to plan their activity over time, by dividing the concession into different management series and through the production of forest inventories. Moreover, participatory mapping activities with local communities help identify the areas of the concession devoted to community development and small-scale agriculture. 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 and thus is without new logging roads. Last, the definition of community-development series should limit forest clearing for agricultural activities and settlement expansion in predefined areas.

Second, FMPs involve concession monitoring in order to control the expansion of settlements and agricultural areas, as well as illegal activities. This includes 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 reduce illegal activities such as slash and burn agriculture, hunting and the illegal harvesting of timber or fuelwood, which could produce deforestation through forest clearing, repeated forest exploitation or even fire spread.

Third, FMPs involve the planning of logging tracks, log landings and skid trails. The main technical intervention here is 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 objectives are to reduce the areas occupied by logging tracks, log landings and skid trails. This is expected to reduce deforestation and the damage to forest cover linked to logging.

Fourth, FMPs involve the adoption of a set of improved forestry-management practices and logging techniques, mainly (i) the application of a minimum log diameter (over the legal minimum) that should reduce the volume and increase the variety of logged species, reducing the pressure on the individual 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 affect forest degradation, but should also reduce deforestation by preventing large canopy gaps and tree-felling in sensitive areas that may require long recovery times.

Finally, through the associated social measures, FMPs 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 fuelwood 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, 2007; Rist et al., 2011), potentially increasing deforestation (Blackman et al., 2018).

FSC certification is hypothesized to affect deforestation through the same causal mechanisms as noted above. In addition, FSC certification should also enhance monitoring by external actors, including independent certifying bodies, NGOs and the media (Blackman et al., 2018). In the context of weak governance, this should result in better compliance with and performance of each of these mechanisms. To the extent that the enforcement of sustainable forest-management practices by regulators in the study area is weak, we may expect to find a greater fall in deforestation in concessions that are FSC-certified.

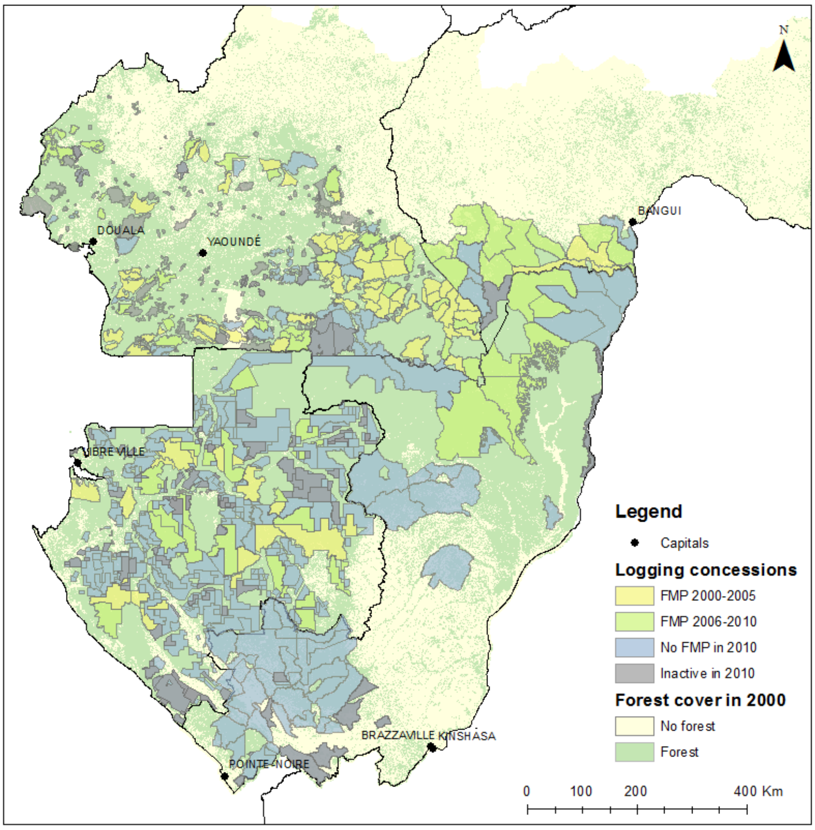
By their nature, these mechanisms are likely to produce effects over different time frames and in distinct areas inside concessions. At first, the planning and monitoring of concessions, as well as improved livelihoods, would likely produce effects that are visible in the short to medium term in areas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

3 Datasets

We here use two types of information to evaluate the effect of sustainable forest-management practices promoted via FMP and FSC.

We initially collected detailed information on logging concessions in the study area using the official land-tenure data released by the OFAC and World Resources Institute (WRI) in the "Congo Basin Forest Atlases". The datasets used in this study cover 397 concessions across the four countries under consideration (see Map 1). The resulting database was updated using the gray literature and information collected on the ground from local actors, especially in the case of concession reallocation to another company during the study period.

Map 1. Location of concessions in the countries analysed in the Congo Basin



To establish when a logging concession started implementing its FMP, we rely on the FMP-acceptance date, despite there being potentially long delays between FMP preparation, submission and acceptance by the competent authorities. We likewise used the issuance date of the FSC certificate to identify logging concessions whose practices have been verified and certified by an FSC-accredited external agent. As logging concessions may introduce sustainable forest-management practices ahead of FMP validation, we will underestimate the FMP effect as some no-FMP concessions in 2010 will already have a FMP in action. We explore some of these implications in Section 6 when considering the limits of our work. Other information collected on logging concessions include the physical attributes of their environment (altitude, steepness and biomass) and their proximity to road infrastructures and settlements, which can affect both the likelihood of adopting sustainable forest-management practices and competition over forest resources and deforestation.

The second type of information comes from high-resolution maps of forest cover and forest-cover changes across the Congo Basin. These come from two sources. We first requested and obtained the original maps produced as part of the global effort to reduce emissions from deforestation and forest degradation in the Congo Basin. 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 programme, 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 the map in the SI).

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**
RCA	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 its sustainable forest-management practice status to the high-resolution deforestation maps informs us about the deforested area over 1990-2000 and 2000-2010 in each concession. However, the raw comparison of the area deforested to time of FMP-acceptance or FSC certificate-issuance is unsatisfactory for at least two reasons. First, logging concessions had their FMP accepted and received their FSC certificates at different points in time. Hence, in line with the theory of change, we need to take the appropriate definition according to the treatments in which we are interested. Second, the decision to adopt sustainable forest-management practices and submit an FMP is initiated by the logging companies, and is thus to some extent endogenous. The concessions that chose to adopt sustainable forest-management practices likely differ from those that did not, and these differences can affect deforestation. There is thus selection bias in the raw comparisons of logging concessions with and without an FMP, so that we risk attributing the effect of other observable or unobservable concession characteristics to sustainable forest-management practices. 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 sustainable forest-management practices.

4 Empirical framework

Following the theory of change outlined above, we wish to evaluate how deforestation in a concession changes with the adoption of sustainable forest-management practices, measured either by FMP-acceptance or FSC certificate-issuance. We would furthermore like to differentiate the short- and medium- to long-term impacts of sustainable forest-management practices. Finally, we will look for spatial heterogeneity in the average treatment effects.

4.1 Treatment groups

The first logging concession in the study area had its FMP accepted in 1999. We hence focus on the impact of (i) having an FMP accepted between 2000 and 2005, (ii) having an FMP accepted between 2006 and 2010 and (iii) obtaining an FSC certificate between 2000 and 2010 on deforestation between 2000 and 2010.

Measuring the effect of the early adoption of sustainable forest-management practices (treatment *FMP 2000-2005*) reflects the potential FMP impact on deforestation over the medium to long run. We expect the concessions with an accepted FMP before 2005 to adopt selective logging practices over at least five years, so that deforestation between 2000 and 2010 will be lower than in concessions without an FMP over this period (See Figure S1). However, as very few concessions had an accepted FMP in 1999, our data do not allow us to measure the impact of FMPs over longer time periods.

We next consider more treated concessions, defined as those that had an FMP accepted between 2006 and 2010 (treatment *FMP 2006-2010*). As deforestation is measured in 2010, this treatment reflects the short term, and supposes that logging companies began improving their forest management before FMP acceptance, as otherwise the time period is too short for us to observe a reduction in deforestation. There may be a long delay between FMP preparation, submission and acceptance by the competent authorities, and concessions may begin to implement FMP activities before its acceptance. The effects of the FMP may thus already be apparent in 2010.

In both of these two treatments, the control group is active concessions without an FMP. We define a concession as "active" if it was attributed to a logging company for at least two years for the *FMP 2000-2010* 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). The "no-FMP concessions" hence include all the active concessions that had no FMP in 2010 (in 2005, respectively, for the *FMP 2000-2005* treatment), including concessions with accepted FMP after 2010 or that had an FMP in process in 2010. For the *FMP 2000-2005* treatment, concessions that had an FMP accepted between 2005 and 2010 were excluded.

Overall, there are 60 FMP concessions and 166 no-FMP concessions for the *FMP 2000-2005* treatment and 121 FMP concessions and 194 no-FMP concessions for the *FMP 2000-2010* treatment (see Appendix 1 for more details).

Despite the certification of sustainable forest-management practices being recent in the Congo Basin, with the first certificates only issued in 2005, we can estimate the impact of FSC certification (the *FSC 2000-2010* treatment) on 2000-2010 deforestation. Since the first FSC certificates were issued in 2005, we here evaluate the short-term impact of FSC certification (after one to five years of certification). It is however worth noting that all FSC-certified concessions already had a valid FMP. Furthermore, over half of the concessions with FSC certificates had an accepted FMP before 2005. As such, estimating the effect of FSC-certificate issuance is similar to measuring the impact of an FMP, but with these particular logging concessions in addition benefiting from third-party verification of sustainable forest-management practices. The treated group here is all active concessions that were certified before 2010. As in the previous treatments, the control group is all active concessions without an FMP in 2010. There are 25 FSC concessions and 194 no-FMP concessions in this treatment.

4.2 Econometrics and identification strategy

This subsection describes the strategy used to account for the endogenous selection of logging concessions into the adoption of sustainable forest-management practices described in Section 3. 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 Y_1 and Y_0, where Y_1 is the area deforested between 2000 and 2010 for logging concessions with an FMP (or with FSC certification) and Y_0 the analogous figure for concessions without an FMP (FSC certification). T is a dummy for the concession having either an FMP or FSC certification. We want to estimate the average effect of an FMP or FSC certification in the concessions that have them, i.e. the average treatment effect on the treated (ATT):

$$\mathrm{ATT} = \tau = \mathrm{E}(\mathrm{Y}_1 - \mathrm{Y}_0 | \mathrm{T} = 1)$$

As Y_0 is never observed for a "treated" concession, the ATT cannot be directly estimated. Denote by X a set of characteristics that are known to affect both deforestation and the presence of an accepted FMP or FSC certificate (which we refer to as the treatment for brevity below). The propensity score is $p(\mathrm{X}) = \Pr(\mathrm{T} = 1|X)$ and $p^* = \Pr(\mathrm{T} = 1)$ is the probability that a concession be treated. The following assumptions, often referred to as "strong ignorability" (Rosenbaum and Rubin, 1983), imply that controlling for X suffices to eliminate all of the confounding factors:

$$\text{(H1) } \mathrm{Y}_1, \mathrm{Y}_0 \perp\!\!\!\perp \mathrm{T}|\,\mathrm{X} \quad \text{and (H2) } 0 < p(\mathrm{X}) < 1.$$

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

$$\mathrm{E}(\mathrm{Y}_0|\mathrm{T} = 1, p(\mathrm{X})) = \mathrm{E}(\mathrm{Y}_0|\mathrm{T} = 0, p(\mathrm{X}))$$

H2 implies that, for almost all values of X, both treated and untreated concessions have a probability of an accepted FMP or FSC certification at some point. If H1 and H2 hold, then Abadie and Imbens (2016) suggest estimating the ATT τ as follows:

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

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 T_i a dummy for the concession i being treated. The matching set $\mathcal{J}_M(i)$ is defined as follows:

$$\mathcal{J}_M(i) = \left\{ j = 1, \dots, N: T_j = 1 - T_i, \left(\sum_{k: T_k = 1 - T_i} \mathbb{1}\langle |p(X_i) - (X_k)| \leq |p(X_i) - (X_j)| \rangle \right) \leq M \right\}$$

where $\mathbb{1}\langle \quad \rangle$ 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 that are known to be correlated with the likelihood of deforestation and the adoption of sustainable forest management to estimate the propensity scores (Blackman, 2013). The selected covariates include indicators of accessibility, population pressure, biomass productivity, average steepness and elevation. Four variables were used to proxy various dimensions of accessibility that are the most correlated with deforestation and the likelihood of adopting sustainable forest-management practices: 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 (for example, forests from Southern Congo have less biomass than those in the Northern Congo, where most of the FMP concessions are located). 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 the supplementary information for more information 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 can affect both the likelihood of deforestation and the adoption of sustainable forest-management practices 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) are hard to measure (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 identification 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 assess impact heterogeneity via pixel-level analyses, which allows us to consider spatial heterogeneity in the average treatment effect inside concessions (see the SI for detailed information on the pixel-sampling strategy). This pixel-level data comes from the high-resolution satellite imagery described in Section 3.

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 settlements (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 accepted between 2000 and 2005, where the expected impact of each mechanism is more likely to be seen.

Table 2: Predictions of the main falsifiable pathways through which sustainable forest-management practices can affect deforestation in the short to medium run

Variables tested in the heterogeneity analysis	Mechanism tested	Expected impact
Distance to previous 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 transport networks	Effectiveness of concession monitoring with 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 concessions' "social contracts"	

5 Results

5.1 The impact of sustainable forest-management practices on deforestation

Figure 2. Difference before and after matching across treatment groups

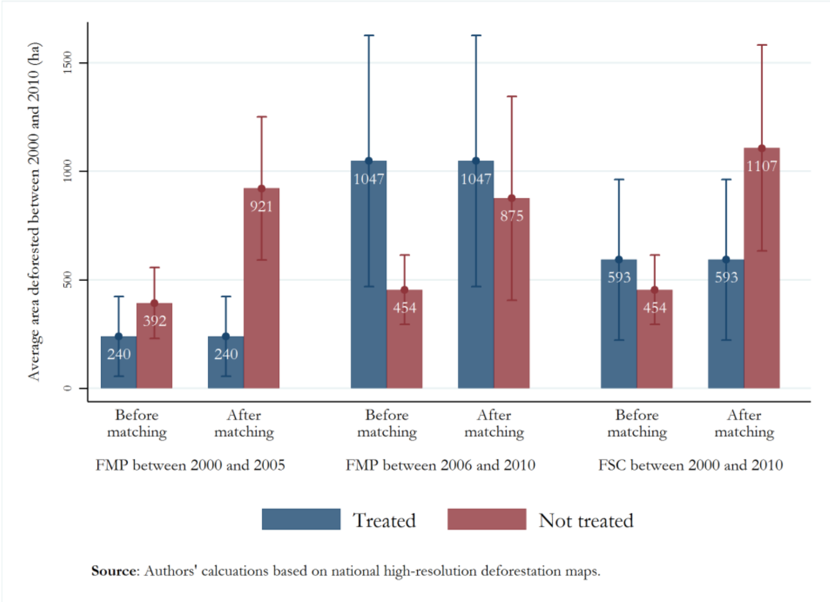
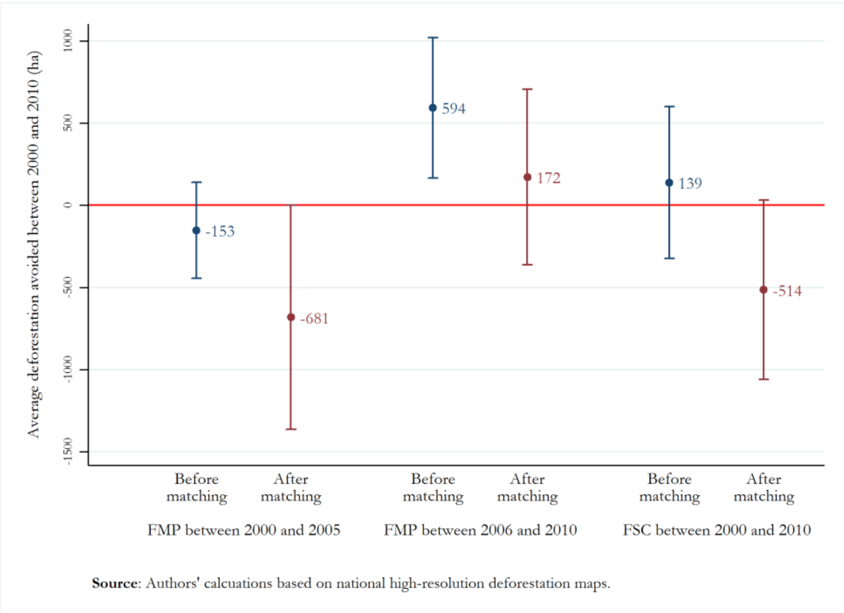


Figure 3. The impact of treatment on 2000-2010 deforestation



After matching, our estimates suggest that concessions with an accepted FMP between 2000 and 2005 have less deforestation compared to otherwise-similar concessions without an FMP. More precisely, FMP adoption between 2000 and 2005 is associated with average lower deforestation of 681ha per concession (Fig. 3). Since the area deforested between 2000 and 2010 is estimated at 921ha in control concessions, this represents a 74% fall in deforestation (Fig. 2). We find similar results using estimates of the area deforested from the GFC dataset, with FMP adoption between 2000 and 2005 being associated with lower deforestation of 1005ha for tree cover of 70% and 1144ha for tree cover of 30%, representing respectively drops of 74 and 75% (see the SI).

For an accepted FMP between 2006 and 2010, after matching, we find no statistically-significant impact of the FMP 2006-2010 treatment 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 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 fall in deforestation between 2000 and 2010. Concessions with FSC certification, testifying that sustainable forest-management practices have indeed been implemented, have on average 514ha less deforestation between 2000 and 2010. Compared to the average deforested area of 1107ha in the control concessions, this represents a drop of 48% (Figs. 2 and 3). This result can be replicated using deforestation from the GFC data, with avoided deforestation in FSC 2000-2010 concessions of 699ha for tree cover of 70% (a 47% fall) and 789ha for tree cover of 30% (a 50% fall).

5.2 Robustness checks

The validity of the above results rests on the assumption that the matching was successful in comparing treated and untreated concessions with similar propensity scores. We moreover assume that no variables other than the 10 covariates used as controls predict FMP acceptance and/or FSC certification and deforestation in logging concession. In this subsection we discuss the sensitivity of our estimates to these two assumptions.

The matching was first successful in balancing treated and untreated households with similar propensity scores. The Figure in the SI shows that the distribution of propensity scores after matching is identical for treated and the untreated control concessions.

However, even after matching, control concessions cover larger tracts of land. The fact that concessions without an FMP cover larger areas than those with an FMP after matching may suggest that our estimate over-estimates the drop in deforestation from the FMP as larger concessions are more likely to have larger areas deforested, even with lower deforestation rates. However, this is not the case: further analyses show that the 2000-2010 deforestation rate is also lower in concessions with an accepted FMP between 2000 and 2005.

There is no statistically-significant difference in past deforestation (1990-2000) for concessions with and without an FMP (although concessions with an accepted FMP between 2000 and 2005 exhibited qualitatively less 1990-2000 deforestation).

We introduce an alternative specification to account more directly for this 1990-2000 deforestation difference, which may reveal subtle but real differences in unobservable characteristics. This seeks to measure the effect of FMP adoption on the ability of logging concessions to reduce deforestation 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 FMP 2000-2005 treatment (see the SI). We applied the same approach for our other treatment variables, and found similar statistically-significant results.

5.3 Impact heterogeneity

We first reproduce our analysis at the pixel rather than the previous concession level, and find that pixels located in treated concessions are less likely to be deforested than those in concessions without an FMP, as in the previous Sections.

Second, spatial-heterogeneity analysis using the pixel-level database revealed that 2000-2005 FMP produced significantly less deforestation in areas close to settlements and previously-deforested areas, with the measured effect being stronger for observations below the median value of these two variables (see Table 3). The ATT for all concessions was a fall of 0.29 percentage points, equivalent to

55% less deforestation; the analogous figures in areas close to settlements are 0.49 (62%) and in areas close to previous deforestation 0.51 (66%). Conversely, the effect of FMP in areas further from settlements and areas of previous deforestation was smaller and insignificant. However, we find no heterogeneity by distance to the main transport networks: the effect is a fall of 0.27 percentage points close to the transport network and 0.19 percentage points further away, both statistically significant but similar to the overall ATT figure of 0.29.

These results are in line with our expectations from our theory of change (Table 2 and Figure 1). They emphasize the effects of improvements in, first, the planning of the concessions, especially for rotation cycles and areas for community and agricultural development, and, second, the monitoring of concessions by closing former logging roads and monitoring the extension of settlements and agriculture areas. Only the monitoring of the incursion of public roads into concessions does not appear to have an effect on the reduction in deforestation.

Table 3. The effect of 2000-2005 FMPs on 2010 deforestation: Geographic heterogeneity

	Coef.	Robust std error	P>|z|	[95% Conf. Interval]	
Overall impact in concessions	-0.00285***	0.00057	0.0000	-0.00398	-0.00173
Heterogeneity:					
Closer to settlements (< 10km)	-0.00486***	0.00098	0.0000	-0.00677	-0.00677
Further from settlements (>= 10km)	-0.00059	0.00070	0.3990	-0.00197	0.00078
Closer to previous deforestation (< 4km)	-0.00508***	0.00088	0.0000	-0.00681	-0.00336
Further from previous deforestation (>= 4km)	0.00004	0.00064	0.9480	-0.00120	0.00129
Closer to main transport network (< 15km)	-0.00268***	0.00103	0.0090	-0.00470	-0.00066
Further from main transport network (>= 15km)	-0.00189***	0.00068	0.0050	-0.00321	-0.00056

Note: *p<0.1, **p<0.05, ***p<0.01.

6 Discussion and concluding remarks

Curbing tropical deforestation is arguably one of the main environmental challenges. 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 adopt sustainable forest-management practices in the Congo Basin. Deforestation is lower in concessions that have had an FMP for at least five years. Like Panlasigui et al. (2018), this highlights the importance of the time frame: interventions aimed at increasing FMPs and FSC-adoption should be evaluated over long time periods.

Evidence from micro-level analyses suggests that FMP have allowed concessions to avoid the overexploitation of previously-logged areas. Our results also suggest that FMP concessions 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 adoption of sustainable forest-management practices. These results confirm the utility of potential spatial heterogeneity in policy and management interventions (Bruggeman et al., 2018).

While FMP acceptance is mandatory across countries in the Congo Basin, logging concessions chose when to draft and submit their FMP. It is then possible that concessions that had their FMP accepted earlier have unobserved characteristics that led them also to deforest less. Our efforts to account for this were limited by the fact that logging concessions change ownership 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 FMP adoption. Whether deforestation will also be lower in logging concessions that had their FMP accepted later remains an open question. Will we continue to see lower 2005-2015 deforestation in concessions with an FMP accepted between 2005 and 2010? Will there continue to be lower deforestation in concessions that had their FMP accepted earlier?

Answering the above questions is a natural extension of our work here, and will help address the external validity of our results. This will also help inform us whether the adoption of sustainable forest-management practices works for all concessions, and how lower deforestation varies over longer time periods. Likewise, the adoption of sustainable forest-management practices is also expected to bring benefits other than reduced deforestation. These include, for example, conservation values such as reducing forest degradation, 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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Figure 1. Theory of change