Electrification and forest loss in Côte d'Ivoire

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Abstract

This paper aims to investigate the impact of electrification on household practices linked to deforestation, such as the size of arable farms and biomass fuel consumption, in Côte d'Ivoire. First, we develop a theoretical framework based on the agricultural households heterogeneous framework by Angelsen (1999) to articulate a potential theoretical link between electrification and the expansion of arable farms. Second, using the most recent four waves of the household Living Standards Measurement Surveys (1998, 2002, 2008, and 2015) and a pseudo-panel fixed effects regression model, we demonstrate that an increased rate of electricity access significantly reduces both the average size of arable farms and biomass fuel consumption (specifically, firewood collection from forests). Our findings remain robust across various alternative specifications (time FE inclusion; time trends inclusion; cocoa price trends inclusion; probit model; entropy balancing; IPW regression adjustment; nearest-neighbor matching; and propensity-score matching). Additionally, we identify an electrification threshold of 80%, beyond which electrification tends to increase the size of arable farms in the country.

JEL Classification: O13, C23, C19

Keywords: Electrification, arable farms, Biomass fuel, Pseudo-panel, Impact assessment methods.

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1 Introduction

In the last century, the forested area of Côte d'Ivoire has declined significantly, dropping from approximately 16 million hectares to less than three million hectares. Today, only around 500,000 hectares of primary forest persist[1]. A December 2018 report by REDD+ attributes 62% of the deforestation to agriculture, surpassing timber exploitation (18%) and infrastructure expansion (10%). Indeed, Côte d'Ivoire is the world's largest cocoa bean producer, contributing 40% to global production, and sustains the livelihoods of 20% of its population. Notably, cocoa and its derivatives constitute half of the country's total exports, as reported by the World Bank. Despite these economic benefits, the Forestry Development Company of Côte d'Ivoire (SODEFOR) has identified that the expansion of cocoa plantations has led to the destruction of over 200,000 hectares of forest. Biomass fuel consumption, particularly firewood and charcoal, contributes also to forest loss, constituting around 80% of the country's total energy consumption. This demand has led to depleted natural forests, causing soil erosion and biodiversity loss. In response, the Ivorian government initiated a 2011 electrification program, including PRONER, PEPT, and a recent 20% tariff reduction for low-income households, with an estimated investment of up to 6,800 billion FCFA (10.4 billion euros) from 2014 to 2030.

This paper aims to explore the links between electricity access and forest depletion in Côte d'Ivoire. Specifically, it seeks to present new evidence regarding the relationship between electrification and household behaviors contributing to forest loss, such as biomass fuel consumption and the size of arable farms in the country. The key questions addressed include: How does electricity access impact biomass fuel consumption in Côte d'Ivoire households? What influence does electricity access have on the size and expansion of arable farms in the country? Additionally, to what extent does the provision of electricity in rural areas lead to changes in household practices contributing to forest loss? Answering these questions can assist policymakers in comprehending the underlying mechanisms, enabling them to implement effective complementary policies for enhancing electricity access while minimizing forest loss in the country.

There is a growing body of literature exploring the factors behind deforestation, with a specific focus on the role of electrification. However, evidence on the relationship between electrification and forest loss in developing countries remains limited. Moreover, conflicting findings in the literature, as seen in studies like Geist and Lambin, 2002 Vs Tanner and Johnston, 2017, contribute to uncertainty regarding this relationship. On one hand, expanding the electricity network or enhancing agricultural profitability through electrification might contribute to forest loss (Geist and Lambin, 2002; Villoria et al., 2014). Conversely, electrification could also reduce the necessity to expand arable farms or collect firewood, potentially mitigating forest loss (Tanner and Johnston, 2017; An et al., 2002; Mensah and Adu, 2015).

We contribute to this growing body of literature in three different ways. First, we document how electrification could affect households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size) by focusing specifically on the case of households in Côte d'Ivoire. This is a contribution to Tanner and Johnston (2017)'s macro (country-level) approach. Second, we adapt Angelsen (1999)'s theoretical framework and explore a potential link between electrification and households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size) from a theoretical point of view. Finally, using the last four waves of the nationally representative households' Living Standards

[1]Source: Inventaire Forestier et Faunique de la Côte d'Ivoire 2021.

Measurement Surveys (1998, 2002, 2008 and 2015) and a pseudo-panel fixed effects regression model with robust standard errors, we document that the electricity access rate significantly reduces both arable farms size and biomass fuel consumption (firewood collection from the forest), providing further empirical evidence in this growing body of literature. Our findings are robust to various alternative relevant specifications (time FE inclusion; time trends inclusion; cocoa price trends inclusion; probit model; entropy balancing; IPW regression adjustment; nearest-neighbor matching; and propensity-score matching). We also document that there is an electrification threshold of 80% beyond which the effect of the electrification would be to increase arable farms size. So increasing electrification without some supportive policies would potentially increase forest loss within the most urbanized localities in the country.

The rest of the paper is divided into four main sections: section 2 presents the literature review, section 3 presents the theoretical link between electrification and household practices potentially contributing to forest loss. Section 4 presents our empirical analysis which includes the main data and variables, some stylized facts, the empirical modeling and the empirical results. Section 5 presents our concluding remarks.

2 Related literature

We have divided this literature review into three sub-sections: (i) traditional causes of forest loss, (ii) effects related to access to electricity, and (iii) potential links between electrification and forest loss. The literature on the traditional causes of forest loss and on the effects resulting from electrification is fairly substantial, unlike that in the third sub-section, devoted to the relationship between electrification and forest loss. We found very few studies documenting this relationship, and no studies dealing with Côte d'Ivoire or even with the West African zone as a whole.

2.1 Traditional causes of forest loss

As mentioned above, the literature on the direct and indirect causes of forest loss is quite abundant. Among the most influential studies is that by Geist and Lambin (2002) which documents the direct and indirect causes of forest loss. For these two authors, factors such as the extension of infrastructure (roads, electricity supply networks, etc.), the expansion of agriculture, wood extraction (wood exploitation, firewood, charcoal, etc.) directly impact forest cover. They also point out that demographic (density, migration and population distribution), economic (market size, urbanization, price changes, etc.), technological (changes in agricultural techniques), political and institutional (corruption, property rights) and cultural factors can indirectly affect forest loss.

Several other studies particularly single out infrastructure expansion. Based on a land use model, Chomitz and Gray (1999) document that infrastructure (e.g. roads) increases agricultural expansion (especially commercial agriculture) because it facilitates access to markets. Therefore, while such infrastructure can reduce poverty, it also increases forest loss and induces environmental degradation. Similarly, in a meta-analysis of the causes of tropical forest loss, Angelsen and Kaimowitz (1999) document that a fairly large transport network –and therefore higher prices for agricultural products– generally leads to more forest loss. The other major source of forest loss is lack of opportunity in the non-agricultural sector, which keeps much of the labor force in plantations. Indeed, Angelsen (2010) argues, on the basis of a meta-analysis of

140 economic models of forest loss, that lack of non-agricultural employment is one of the main causes of forest loss. Angelsen and Kaimowitz (1999) document from a meta-analysis of the causes of tropical forest loss that low wages and a shortage of non-agricultural employment generally lead to more forest loss. The creation of employment opportunities in non-agricultural sectors would therefore help to safeguard much of the forest.

Armed conflicts are also detrimental to the preservation of forests. For example, in their analysis of the dynamics of the designated forest of Haut-Sassandra (Côte d'Ivoire) in a post-armed conflict situation, Sangne et al. (2015) found that the area, once considered one of the country's best protected designated forests, was experiencing several intrusions into its historical boundaries as a result of the country's military-political crisis that lasted from 2002 to 2011. Numerous pioneering fronts were opened, leading to the clearance of several thousand hectares of natural forest (formerly controlled by rebel armed groups from the north) followed by the plantation of cash crops (mainly cocoa).

Other variables such as property rights, fiscal policy, the real exchange rate or agricultural productivity could have an impact on the dynamics of forest loss. According to Liscow (2013), the effects of property rights would be to increase forest loss. Using the example of Nicaragua, he found that property rights encourage investment, which leads to improved agricultural productivity and thus to forest loss. Indeed, improving productivity increases agricultural profit and thus the incentive to expand arable farms at the expense of forests .

Foster and Rosenzweig (2002) point out that fiscal measures such as lowering timber import tariffs can decrease forest loss at the national level. However, this only shifts the source of wood supply, thus increasing forest loss elsewhere in the world. Arcand et al. (2008), using a sample of 101 countries covering the period 1961-1988, point out that: (i) lower discount rates and stronger institutions reduce forest loss, (ii) a depreciation of the real exchange rate increases forest loss in developing countries and reduces it in developed countries, and (iii) paradoxically, better institutions can exacerbate the deleterious effect of real depreciation in developing countries. Finally, it is important to focus on the role of agricultural productivity on the phenomenon of agricultural land expansion, which is the main source of tropical forest loss. According to Gibbs et al. (2010), agricultural expansion (especially commercial agriculture) is one of the major causes of tropical forest loss. Similarly, Hertel (2012) resurrects the Borlaug Vs Jevons debate on the effects of agricultural productivity on land use. According to Borlaug (2002), agricultural innovation leads to parcels of land being saved when demand for agricultural products remains inelastic (fixed). He supports the idea that improved farming techniques lead to increased agricultural production and an improved environment. In the same vein, Abman and Carney (2020) provide evidence that subsidized fertilizer increased agricultural productivity and reduced pressure to expand agriculture into forest margins in Malawi. Their results suggest that policies aimed at increasing small-scale agricultural productivity may have positive environmental spillovers. Contrary to Borlaug's idea, based on the Jevons paradox, an improvement in agricultural productivity is accompanied by an expansion of the cultivated area.[2] Rudel et al. (2009) have also been critical of Borlaug's idea. Looking at FAO (Food and Agriculture Organization) data for 961 agricultural sectors in 161 countries over a 15-year period, they find no significant decline in agricultural area as a result of increased crop yields.

[2]The Jevons paradox implies that since technical progress improves the efficiency of the use of a resource, the total consumption of that resource may increase rather than decrease.

2.2 Effects related to access to electricity

In addition to its contribution to development and the improvement of people's well-being, access to electricity is placed at the heart of the Millennium Development Goals, particularly by international development organizations such as the United Nations (UN) and its Development Programme (UNDP). A large number of studies have established a positive relationship between access to energy and the level of economic development (Ferguson et al., 2000; Wolde-Rufael, 2006). Energy also accelerates structural transformation, notably by promoting industrial development (Rud, 2012). Electricity is the form of energy most closely associated with the vectors of economic development (Lee et al., 2020; Stern et al., 2019).

Indeed, electricity increases firms' productivity, reduces production costs and increases the producer's surplus and income (Rud, 2012; Fisher-Vanden et al., 2015; Allcott et al., 2016). In addition, it significantly improves the situation of households, especially in rural areas, through agricultural productivity, income growth, education, health and off-farm employment opportunities (Esteban et al., 2018; Kanagawa and Nakata, 2008; De Gouvello and Durix, 2008 Lipscomb et al., 2013; Dinkelman, 2011; Grogan and Sadanand, 2013; Lipscomb et al., 2013; Khandker et al., 2009; Khandker et al., 2014). Access to electricity also has a fairly significant impact on the demographic dynamics of rural areas. Thus Peters and Vance (2011) suggest, based on ENV (Living Standards Surveys in Côte d'Ivoire) data, that electrification increases the fertility rate for urban households and reduces it for rural households.

2.3 Potential links between electrification and forest loss

Although relatively few previous studies have provided evidence on the impact of electrification on forest loss, one of the most influential is that by Tanner and Johnston (2017). Using a panel of 158 countries for the years 1990, 2000 and 2010, the authors find that rural electrification reduces forest loss and better explains this phenomenon compared to factors such as population growth or development. Moreover, electrification often acts indirectly on forest loss, notably through the adoption of new techniques requiring electricity. This is illustrated by Shively and Pagiola (2004) who find that improvement of irrigation systems in the Philippines would have made it possible to reduce forest loss by half. They explain this by the fact that extensive farmers, who are not very competitive with the intensive farmers who have benefited from this improvement, are being squeezed out of the market. Also, Angelsen et al. (2001) argue that the adoption of new technologies could reduce the need to expand farms. On the other hand, Villoria et al. (2014) suggest that the promotion of agricultural innovation could improve agricultural profitability and thus encourage forest loss through the expansion of agricultural land.

Finally, many studies have documented that electricity is a substitute for firewood outside Africa. Apart from Akpandjar and Kitchens (2017) which found that electrification led to a shift away from the use of firewood for cooking by Ghanaian households over the period 2000 to 2010, this is not necessarily the case in Africa because cooking with electricity requires stoves, which are still relatively expensive for the majority of poor households, especially in sub-Saharan Africa. However, it is conceivable that this substitution could take place, indirectly, through other channels such as household appliances. It is known, for example, that a large proportion of households in rural Africa have recently acquired refrigerators, which could optimize food preservation and thus reduce the demand for firewood and charcoal for cooking. Furthermore, electrification of a rural locality could help to develop a market for butane gas, for example, or even alternative energy sources, which could possibly reduce the pressure on forest resources for cooking.[3] Electrification could also reduce the amount of firewood used for cooking without necessarily replacing firewood with other types of fuel such as electric stoves or butane gas. The reason is that with electric light, women can prepare the main meal just before it is eaten rather than preparing it during the day and then reheating it in the evening.

3 Theoretical link between electrification and household practices potentially contributing to forest loss

This section aims to theoretically document the link between electrification and households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size).

3.1 Conceptual links between electrification and practices potentially contributing to forest loss (firewood collection and arable farms size)

In this analysis, our intuition (Figure 1) is that electricity could affect households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size) in Côte d'Ivoire. Indeed, electrification, notably via irrigation techniques and/or borehole drilling systems, might have a positive effect on agricultural yield.

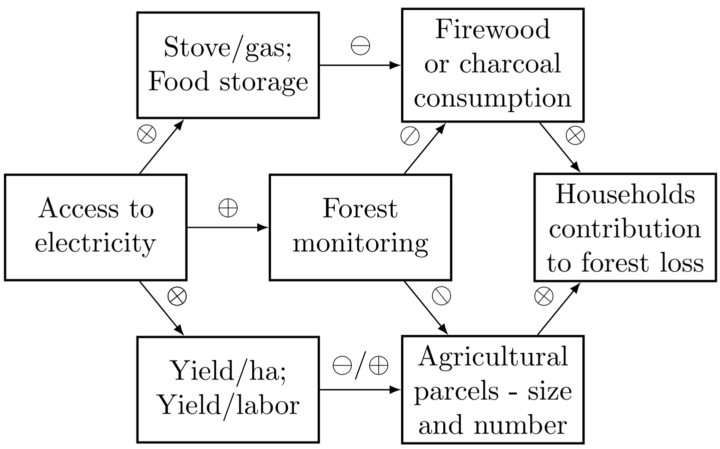

Figure 1: Conceptual model of the interrelationship between electrification and households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size)

Notes: ⊕ indicates expected positive relationship, ⊖ indicates expected negatives relationship and ⊖/⊕ indicates an ambiguous relationship (positive relationship or negative relationship, depending on the prevailing market structure).

However, the impact of agricultural productivity on the size of arable farms remains rather ambiguous, especially in view of the Borlaug vs Jevons debate. According to Borlaug (2002)'s hypothesis, improved agricultural productivity leads to an economy of land when the demand for agricultural products remains inelastic (fixed). However, according to Jevons' paradox, an improvement in agricultural productivity is

[3] Butane gas is one of the main energy sources for cooking in Côte d'Ivoire.

accompanied by an expansion in the area of cultivated land. We also believe that electrification of a locality could accelerate its structural transformation by creating new off-farm employment opportunities (Chhay et al., 2020; Dinkelman, 2011). This would free up agricultural labor for these new sectors. Thanks to the complementarity of factors, this would tend to broadly reduce arable farms size. This labor transfer is also valid for the labor force collecting firewood. Moreover, access to electricity encourages the adoption of electric cookers, which would be an alternative to firewood. We could also consider the establishment of a butane gas supply market following the electrification of a locality. Another important element is the acquisition of refrigerators, which generally allows households to optimize food conservation, and therefore to reduce the frequency of cooking (reduction in energy demand for cooking). Finally, the role of forest monitoring in the country should also be highlighted. Forest monitoring in Côte d'Ivoire is carried out by "water and forest" agents, who are government officials. The assignment of these agents to a locality takes into account the basic amenities within that locality, of which electricity is a part. Thus, these agents are present in greater numbers in localities that are electrified than in those that are not.

3.2 Theoretical framework

Our theoretical contribution has been to start from the heterogeneous frameworks approach proposed by Angelsen (1999) and to introduce the electrification variable in order to open a new debate on its potential theoretical links with household activities that can lead to forest loss or degradation in tropical countries like Côte d'Ivoire. Our choice of this heterogeneous framework approach is also justified by Côte d'Ivoire's large geographical disparities. Indeed, major geographical disparities remain between Abidjan (economic capital) and the rest of the country. This polarization and the great differences in terms of development between the country's major zones prevent us from adopting a single economic framework adapted to the case of Côte d'Ivoire (for example the most common agricultural household framework).

The main idea of this type of framework is to progressively include hypotheses, starting from the most basic framework (subsistence economy without market) to arrive at the most comprehensive framework (with markets, property regime, etc.). In appendix A, we present in details and discuss theoretically the most important channels through which we think electricity could affect households practices potentially contributing to forest loss (arable farms size expansion).

We summarize our main theoretical findings in Table 1 below by framework and by channel. We broadly documented that the effect of electrification through demography would accentuate the forest loss of a locality in frameworks I and II (when the migration effect outweighs the natality effect). However, the channel of demography becomes irrelevant as soon as freedom of movement (migration of the labor force) is introduced in frameworks III and IV. Electrification through agricultural productivity is a means of mitigating forest loss in framework I and in framework II (only when the subsistence effect outweighs the farm-firm effect). On the other hand, it becomes a source of forest loss when the subsistence effect disappears (introduction of perfect markets) in framework III and IV. The productivity channel is relevant in all the frameworks we considered. Moreover, the more electrification reduces fallow time (increase in agricultural intensification), the more it reduces forest loss in frameworks I and II. This agricultural intensification channel becomes irrelevant once perfect markets are introduced in frameworks III and IV. Finally, the effect of electrification through both the intensification of forest monitoring and the creation of new employment opportunities would help to fight forest loss in framework II, III and IV (none relevant channels in framework I).

Table 1: Summary of our theoretical findings

	Main transmission channel					
Framework	Demography	Agricultural productivity	Agricultural intensification	Forest monitoring	Off-farm wages	Wages in economy
I	$\nearrow$ (if $\frac{dN}{de} > 0$)	$\searrow$	$\searrow$	n.a	n.a	n.a
II	$\nearrow$ (if $\frac{dN}{de} > 0$)	$\searrow$ (if $X < \frac{C^{min} - wL^{out}}{\alpha}$)	$\searrow$	$\searrow$	$\searrow$	n.a
III	n.a	$\nearrow$	n.a	$\searrow$	n.a	$\searrow$
IV	n.a	$\nearrow$ (if $g > 0; \delta + \lambda > g$)	n.a	$\searrow$ (if $g > 0; \delta + \lambda > g$)	n.a	$\searrow$ (if $g > 0; \delta + \lambda > g$)

Notes: Framework I: Subsistence economy (no labor market) ; Framework II: Chayanovian economy (imperfect labor market) ; Framework III: Open economy with perfect labor market (static open access) ; Framework IV: Open economy with perfect labor market (dynamic open access). $\searrow$ means that electrification reduces forest loss and $\nearrow$ means that electrification increases forest loss given a specific framework and transmission channel. n.a means not applicable.

In other words, framework I indicates that if the migratory effect of electrification on demography does not outweigh the fertility (or natality) effect, then electrification would globally reduce the expansion of arable farms size in rural areas of Côte d'Ivoire. Framework II, through the agricultural productivity channel, highlights the fact that the environmental effect of electrification would decrease following the urbanisation rate (demography) of localities in Côte d'Ivoire. More precisely, electrification would reduces forest loss in rural areas more effectively than in urban areas. Finally, through frameworks III and IV, the favourable effects of electrification on forest loss through other channels (forest monitoring and off-farm employment) would be somewhat mitigated by the unfavourable effect through the agricultural productivity channel.

Although our theoretical section opens a fascinating debate on the potential links between electrification and the arable farms size –potentially leading to forest loss– it does not necessarily allow us to conclude on the overall effect of electrification on arable farms size. Our next empirical section 4 provides a clear answer to this question about the effect of electrification on households practices potentially contributing to forest loss (arable farms size and biomass fuel consumption).

4 Emprical approach

Our empirical analysis includes the main data and variables subsection, some stylized facts, the empirical approach and the empirical results.

4.1 Data and variables: socio-economic data

In this study, we use data from the last four waves of the Côte d'Ivoire nationally representative households' Living Standards Measurement Survey (LSMS or ENV) for the years 1998, 2002, 2008 and 2015.[4] ENV data are provided by the National Institute of Statistics of Côte d'Ivoire. The main objective of an ENV is to collect information to improve the planning and evaluation of economic and social policies in the country. The main variables used in our empirical models are: Access to electricity, Firewood collection, and Arable farms size.

[4]ENV: Enquête Niveau de Vie

To find out whether a household has access to electricity or not, we refer to the question "what is your main source of lighting?". To find out how households cook, we refer to the question: "what is your main source of fuel?". Finally, to find out how much land households farm, interviewers asked households to estimate the size of each arable farms in hectare, hundredths of a hectare or m^2. We converted all the arable farms size into hectares and added up the total per household.

Our analysis also included several relevant control variables such as Household size, Household expenditure, Household head gender, Male/female ratio in households, Possession of a refrigerator and stove, Location, and Development hub.

The average household size was calculated by adding up all household members. The average size of Ivorian households is around 5 people. The per capita average expenditure is around 500 euros per year in the country over the study period. Regarding the household head gender, in Côte d'Ivoire, decisions in households are very often made by men. Our calculations document that the proportion of households headed by men remains high and almost constant despite the recent waves of emigration. In fact, around 4/5 of Ivorian households remained male-headed over the period 1998-2015. Regarding the possession of a refrigerator and stove, on average, over the study period, around 15% of households had a stove and around 20% had a refrigerator, according to our calculations from the ENV data. We also define three main development hubs. The first consists of all households living in and around the economic capital (District of Abidjan). The second consists of all urban households that are not around the city of Abidjan (intermediate cities), and the third consists of all rural households in the country. Finally, we also considered the male/female ratio in households, and the living area binary variable which tells us whether the household lives in a rural or urban area.

4.2 Some stylized facts

Figure 2 below and Figure C1 (see appendix C) compare households connected to electricity with households not connected to electricity. For all surveys and for yearly observations, having access to electricity is negatively correlated with firewood collection and agricultural activities. Specifically, while the share of households collecting firewood exceeds 75% in the unconnected group, it remains just below 30% in the connected group. This difference can also be seen when observing the average size of arable farms. Indeed, the average size exceeds 3 hectares in the group of non-connected households. The average size of arable farms is twice as small in the connected group. The difference between connected and unconnected households in terms of firewood collection and agricultural activities remains verified for all survey years (1998, 2002, 2008, and 2015), see appendix C.

Figure 3 documents some interesting trends at the departmental (county) and regional levels. The first graph in the first row documents that the proportion of households collecting firewood within a department decreases with that department's electrification rate. Similarly, the second graph on the first row documents that the proportion of households owning at least one arable farm decreases with the electrification rate. The third graph on the top row documents that the average size of arable farms also decreases with the electrification rate of the departments. These results are also verified at the regional level (second row).[5]

[5] Côte d'Ivoire has 108 departments and 33 regions.

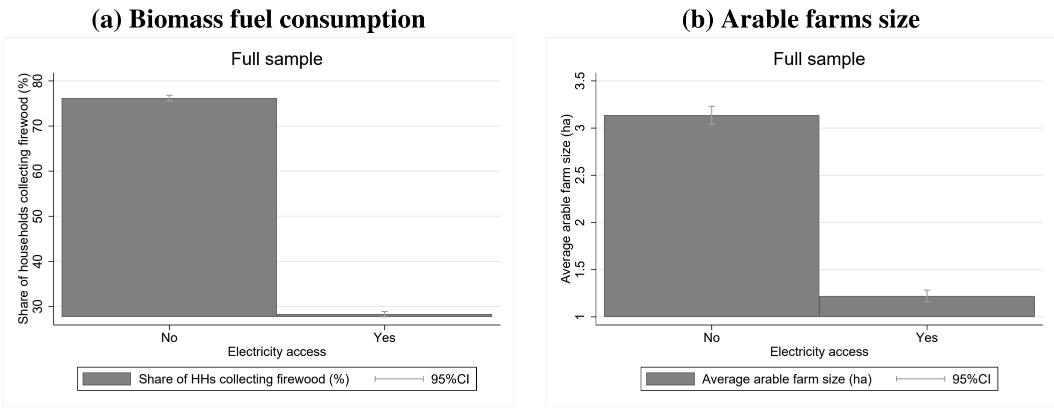

Figure 2: Connected versus non-Connected households (Full sample)

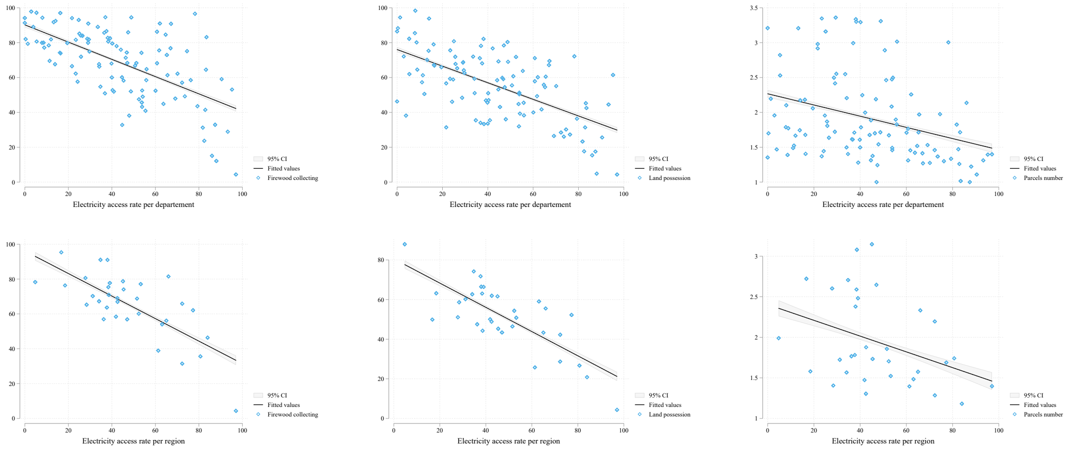

Figure 3: Relationship between electrification and households practices potentially contributing to forest loss (biomass fuel consumption and arable farms size) at departmental and regional level

4.3 Empirical methodology

To confirm the previous stylized facts, we need to consider any potential endogeneity issue of the electrification variable. Indeed, electrification depends on household group-specific factors that may also affect firewood collection and arable farms size. Although we control for observable factors (household size, male/female ratio, expenditure, etc.), there might remain some unobservable factors (household preference, cultural practices, etc.) that could potentially affect the choice of electrification and our two outcome variables, leading to potential endogeneity of the electrification variable. Therefore, the primary objective of the cohort fixed effects in our specification is to capture these unobservables as long as they are fixed over time.

We address this potential endogeneity issue by adopting a pseudo-panel fixed effects regression model analysis. The main purpose for building pseudo-panel is to control for unobserved heterogeneity or group-specific characteristics as in a usual panel data analysis. The role of fixed effects is to account for the impact of group-specific unobservable characteristics on the cohorts of households activities (firewood collection and arable farms size). In other words, fixed effects allow us to isolate the causal effect of electrification on household activities (firewood collection and arable farms size) by removing the potential bias that arises from unobserved heterogeneity.

The pseudo-panel approach is used when formal panel data are not available and when only independent, repeated cross-sectional data are available. A pseudo-panel can be constructed using subgroups of the cross-sectional data (called cohorts). Cohort averages are used as point observations in the pseudo-panel (Deaton, 1985). Each cohort consists of a homogeneous group of individuals that are assumed to share the same time invariant characteristics from one cross-sectional survey to the next, (year of birth, gender, location, degree or level of education, etc.). However, since cohort averages are based on a set of individuals, they are subject to possible measurement errors that can be ignored if the number of individuals in each cohort is sufficiently large. Generally, there is a trade-off between the number of cohorts and their size. A large number of cohorts increases the heterogeneity of the pseudo-panel but decreases the average number of individuals per cohort leading to less precise estimates of cohort averages and vice-versa. As the available data consist of repeated cross-sections of household surveys, we aggregate households into cohorts, by taking the cross-sectional average for each cohort to construct the model variables. In particular, each quantitative model variable z_{it}, is given by the average of observed values of all $\bar{z}_{ct}$ in each cohort c for period t.

The criteria for forming cohorts cannot be chosen at random. It should be remembered that the principle of pseudo-panels is to form cohorts, in other words profiles, grouping together individuals whose behaviour is considered to be similar. A good grouping criterion should: (1) be a characteristic that does not change over time at the individual level, defines a stable sub-population and results from a trade-off that (2) forms sufficiently large cohorts while (3) not losing too much variability. In our case, we established cohorts on the basis of the following time-invariant criteria: the area or location (rural household or urban household), the strata (District of Abidjan, Intermediate Cities, Eastern Rural Forest, Western Rural Forest, Rural Savannah), and the year of birth of the household head (or generation of households). Once the cohorts had been established, the following model is estimated:

$$\overline{\text{Outcome}}_{ct} = \beta_1 \overline{\text{Electricity}}_{ct} + \beta_2 \overline{X}_{ct} + \overline{\alpha}_c + \overline{\varepsilon}_{ct} \tag{1}$$

$\overline{\text{Outcome}}_{ct}$ represents the share of households collecting firewood ($\overline{\text{Firewood}}_{ct}$) or the average arable farms size ($\overline{\text{Farm}}_{ct}$) within a cohort c at year t. $\overline{\text{Electricity}}_{ct}$ represents the electricity access rate per cohort c at year t. $\overline{X}_{ct}$ represents the control variables per cohort c at year t. $\overline{\alpha}_c$ represents cohorts fixed effects and $\overline{\varepsilon}_{ct}$ is the error term. As control variables, we include household characteristics that are likely to impact on electricity adoption, firewood collection and household agricultural decisions. The choice of control variables included in the model is based on previous empirical works on the subject as well as on our theoretical framework. These characteristics include male/female ratio, average household size, migration (approximated by the gender of the household head, female head in this country probably means that the male head has migrated), expenditure levels (a proxy of household wealth), and ownership of equipment such as refrigerators and stoves (access to energy services). We control for household male/female ratio as this may be relevant in explaining both firewood collection and agricultural activities. Indeed, in sub-Saharan Africa, firewood collection is mainly carried out by women. Thus a household composed mainly of men would have a low tendency to collect firewood. In addition, the agricultural labor force in this part of Africa is predominantly male. So a high household male/female ratio could be a key factor in expanding agricultural land. Household size is also relevant in explaining both energy and agricultural choices. Another fairly relevant variable that we control for is the gender of the household head. In this region, households are largely headed by men. Studies have documented that female-headed households are generally households where the male (head of household) has migrated. In addition to the fact that these households benefit from more optimal management by these women, they tend to be the richest (receiving remittances from migrants). This can therefore condition both the energy and activity choices of these households. Finally, we also control for the level of expenditure (a proxy of wealth) and ownership of equipment (energy services) at household level.

4.4 Results

Table 2 presents the effect of electrification rate on the percentage of households collecting firewood and on average arable farms size within cohorts. The results document that the effect of electrification on the percentage of households collecting firewood and on average arable farms size is negative and statistically significant. These main results are obtained by controlling for specific fixed effects, and by considering robust and replications-based standard deviations.[6] The coefficients are obtained using Within estimation taking into account cohort fixed effects (FE), which capture any time-invariant heterogeneity across cohorts.

To our main specification (Equation 1), we also add year fixed effects to control for factors changing over time that are common to all cohorts for a given time period (electoral crisis, coups, etc.). We also add time trend to control for trend variable that affects the dependent variable and is not directly observable but is highly correlated with time (for instance, government ongoing national rural electrification program, other infrastructure expansion programs, land property rights reinforcement in the country, etc.). Finally, as cocoa farming represents the main source of revenue in the country, we add cocoa price index to control for arable farming dynamics in the country as in Berman et al. (2023).

Table 2: The effect of electricity access on firewood collection and arable farms

	Firewood collection						Arable farms size					
	Robust std. err.	Bootstrap std. err.	jackknife std. err.	Time FE	Time trend	Cocoa price Index	Robust std. err.	Bootstrap std. err.	jackknife std. err.	Time FE	Time trend	Cocoa price Index
Electricity access rate	-0.147**	-0.147**	-0.147**	-0.185***	-0.202***	-0.200***	-0.265**	-0.265***	-0.265**	-0.128*	-0.152**	-0.134**
	[0.060]	[0.069]	[0.063]	[0.069]	[0.069]	[0.069]	[0.106]	[0.093]	[0.112]	[0.068]	[0.070]	[0.063]
Male/female ratio	-0.187**	-0.187***	-0.187**	-0.139	-0.106	-0.108	-0.149	-0.149	-0.149	-0.177	-0.247	-0.249
	[0.075]	[0.068]	[0.083]	[0.091]	[0.087]	[0.084]	[0.175]	[0.217]	[0.174]	[0.189]	[0.196]	[0.197]
Households size	-0.011**	-0.011**	-0.011**	0.001	-0.000	0.000	0.005	0.005	0.005	-0.002	-0.008	-0.010
	[0.005]	[0.006]	[0.005]	[0.006]	[0.006]	[0.005]	[0.009]	[0.007]	[0.009]	[0.009]	[0.010]	[0.010]
Male-headed households	-0.076	-0.076	-0.076	-0.046	-0.054	-0.047	0.093	0.093	0.093	0.037	0.062	0.048
	[0.076]	[0.092]	[0.082]	[0.073]	[0.080]	[0.079]	[0.067]	[0.073]	[0.070]	[0.070]	[0.062]	[0.062]
Refrigerator owners	0.017	0.017	0.017	-0.005	0.011	0.004	-0.040	-0.040	-0.040	-0.014	-0.034	-0.022
	[0.035]	[0.042]	[0.038]	[0.032]	[0.037]	[0.038]	[0.037]	[0.038]	[0.039]	[0.041]	[0.034]	[0.033]
Log expenditure	0.012**	0.012**	0.012**	-0.052***	0.001	-0.005	-0.141	-0.141	-0.141	0.069	-0.009	0.029
	[0.005]	[0.005]	[0.005]	[0.014]	[0.004]	[0.004]	[0.093]	[0.104]	[0.095]	[0.073]	[0.073]	[0.072]
Stove owners	-0.071**	-0.071*	-0.071*	-0.065*	-0.070*	-0.073**	-0.012	-0.012	-0.012	0.048	0.006	0.019
	[0.034]	[0.037]	[0.037]	[0.036]	[0.036]	[0.035]	[0.049]	[0.061]	[0.051]	[0.049]	[0.046]	[0.044]
Observations	552	552	552	552	552	552	552	552	552	552	552	552
R^2	0.131	0.131	0.131	0.252	0.203	0.215	0.016	0.016	0.016	0.063	0.033	0.040
ρ	0.897	0.897	0.897	0.886	0.893	0.892	0.284	0.284	0.284	0.284	0.282	0.282

Notes: The table presents our main results by controlling for specific fixed and variable effects, and by considering standard deviations based on replications. The coefficients are obtained using Within estimation taking into account cohort fixed effects (FE), which capture any time-invariant differences across cohorts. Year fixed effects control for factors changing over time that are common to all cohorts for a given time period (electoral crisis, coups, etc.). Time trend control for trend variable that affects the dependent variable and is not directly observable but is highly correlated with time (for instance, government ongoing national rural electrification program). Cocoa price index control for arable farming dynamics in the country. Unreported constant is included. Bootstrap standards errors are based on 200 replications. Jakknife standards errors are based on 138 replications. Robust standards errors permit for the errors to be heteroskedastic and also be correlated with each other within clusters. Robust, Bootstrapped and Jakknife Standard errors in brackets. The intraclass correlation (ρ), documents how much of the variance in the output (firewood collection, arable farms size) is explained by the difference across cohorts. In our case, around 90% for firewood collection and 28% for arable farms size (this difference is essentially explained by the relative higher "Between" variability of 35% for firewood collection compared to 22% for arable farm variable in our sample). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The first side of Table 2 documents that a high electrification rate is associated with a low proportion of households collecting firewood within a given cohort, as the coefficient is negative and significant. More precisely, each increase in the electrification rate per cohort by one unit above the average leads to a decrease

[6] The Robust standards errors permit for the errors to be heteroskedastic and also be correlated with each other within clusters. The Bootstrap standards errors based on 200 replications and the Jakknife standards errors based on 138 replications allow us to rule out any suspicion of over-rejection of the hypothesis that the effect is not significant.

of 0.147% in the proportion of households collecting firewood within the cohort. This result is in line with Akpandjar and Kitchens (2017) who found that electrification led to a shift away from the use of firewood by Ghanaian households over the period 2000 to 2010, and Dendup (2022) who found that electrification reduces firewood consumption by about 0.83–2.09 cubic meters per month in rural Bhutan. This negative relationship persists after controlling for time FE, time trend and cocoa price index.

It can also be seen that household firewood collection is neither explained by the gender of household heads nor by refrigerator ownership. Ownership of a refrigerator is not a key element in reducing the proportion of households collecting firewood. But, one might think that households with a refrigerator can easily conserve their food, thus helping to reduce the frequency of cooking (reduction in the amount of firewood collected). Electrification could also reduce the amount of firewood used for cooking without necessarily replacing firewood with other types of fuel such as electric stoves or butane gas. The reason is that with lighting, households can prepare the main meal just before it is eaten rather than preparing it during the day and then reheating it in the evening. However, firewood collection decreases with the proportion of men, household size and stove ownership. Indeed, in most countries in Africa, firewood collection is mainly carried out by women. Finally, firewood collection increases paradoxically with the level of household expenditure. Our intuition is that, as collected firewood is free of charge, high-spending households, which are in general large households, would collect as much firewood as possible to reduce their energy expenditure, thus their total expenditure.

The second side of Table 2 presents our estimates of the effect of electrification on the average arable farms size within a given cohort as dependent variable. For all our estimates, electrification has a negative and significant effect on arable farms size. Each increase in the electrification rate per cohort by one unit above the average leads to a decrease of 0.265% in the amount of agricultural land within the cohort. It can also be seen that arable farms size is not significantly explained by household size, the gender of the household head, the male/female ratio in the household, the possession of a refrigerator and electric cooker or household expenditure. Our results are in line with those obtained by Tanner and Johnston (2017), Shively and Pagiola (2004) and Angelsen et al. (2001). But they are in contrast to those obtained by Villoria et al. (2014), who raised the idea that the promotion of agricultural innovation could improve agricultural profitability, leading to the expansion of arable farms and thus to increased forest loss.

4.5 Robustness check

4.5.1 Individual cross-sectional analysis

To support the robustness of our pseudo-panel fixed effects regression approach, we first opt for an independent cross-sectional analysis over the full sample and covering each survey wave in the country (1998, 2002, 2008 and 2015). Although this approach leads to the loss of the panel dimension of the first part (pseudo-panel approach), it nevertheless makes it possible to exploit the large number of observations per household (potential gain on the precision of the estimators) and to verify if the grouping of households for the formation of the pseudo-panel in the first part gives coherent results at least in terms of sign of the effects. To predict the probability of a household collecting firewood, we adopt the probit cross-sectional model. According to our results (first side of Table 3), for an average household with access to electricity, the probability of collecting firewood decreases by 28 percentage points for the full sample or over the period 1998-2015 (33.5 percentage points in 1998, 21.6 percentage points in 2002, 31.6 percentage points in 2008 and 19.3 percentage points in 2015). In the second side of Table 3, for an average household with access to electricity, the probability of having at least one arable farm decreases by 23.7 percentage points for the full sample (32.9 percentage points in 1998, 26.9 percentage points in 2002, 17.9 percentage points in 2008 and 19.3 percentage points in 2015). To sum up, although it is difficult to compare the magnitude of these results with our pseudo-panel results because of different econometric specifications, we can nevertheless confirm the negative and significant effect of electrification on our two outcome variables (for the full sample and for each year of survey). Moreover, we also observe a gain in the precision of our estimators (smaller standard deviations).

Table 3: Robustness check – The effect of electricity access on firewood collection and arable farms

	Firewood collection					**Arable farms**				
	Full sample	1998	2002	2008	2015	Full sample	1998	2002	2008	2015
Electricity access (No=0, Yes=1)	-0.280***	-0.335***	-0.216***	-0.316***	-0.193***	-0.237***	-0.329***	-0.269***	-0.179***	-0.193***
	[0.003]	[0.009]	[0.005]	[0.005]	[0.008]	[0.004]	[0.011]	[0.007]	[0.007]	[0.008]
Number of women	0.101***	0.116***	0.045***	0.088***	0.203***	0.067***	0.073***	0.047***	0.029**	0.143***
	[0.006]	[0.015]	[0.007]	[0.010]	[0.016]	[0.006]	[0.017]	[0.009]	[0.010]	[0.017]
Households size	0.026***	0.013***	0.043***	0.031***	0.028***	0.029***	0.019***	0.037***	0.021***	0.030***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.002]	[0.001]	[0.002]	[0.001]	[0.001]	[0.002]
Male-headed households	0.054***	0.046**	-0.019*	0.071***	0.112***	0.111***	0.079***	0.054***	0.083***	0.188***
	[0.006]	[0.017]	[0.009]	[0.010]	[0.012]	[0.006]	[0.018]	[0.011]	[0.010]	[0.012]
Fridge ownership	-0.216***	-0.102***	-0.085***	-0.224***	-0.245***	-0.124***	-0.052*	-0.065***	-0.118***	-0.191***
	[0.010]	[0.022]	[0.015]	[0.019]	[0.023]	[0.010]	[0.022]	[0.015]	[0.018]	[0.023]
Log expenditure	-0.088***	-0.106***	-0.649***	-0.075***	-0.095***	-0.065***	-0.078***	-0.160***	-0.011**	-0.034***
	[0.002]	[0.006]	[0.034]	[0.003]	[0.004]	[0.002]	[0.007]	[0.006]	[0.003]	[0.005]
Stove ownership	-0.342***	-0.118***	-0.223***	-0.405***	-0.384***	-0.215***	-0.100***	-0.187***	-0.217***	-0.230***
	[0.012]	[0.027]	[0.020]	[0.024]	[0.025]	[0.011]	[0.026]	[0.018]	[0.018]	[0.023]
Observations	40498	4200	10799	12600	12899	40498	4200	10799	12600	12899
Pseudo R^2	0.280	0.386	0.522	0.321	0.167	0.182	0.268	0.322	0.128	0.113
Wald chi2	15725.5	2245.2	7817.0	5553.4	2971.7	9894.6	1556.8	4825.4	1793.1	1975.2
Prob > chi2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Year FE	Yes	No	No	No	No	Yes	No	No	No	No

Notes: The table highlights the negative and statistically significant effect of access to electricity on the probability of firewood collection and arable farms ownership at the household level. The result is robust for each survey year and when all survey years are combined. The coefficients represent the average marginal effects based on probit estimates. Unreported constant is included. Standard errors in brackets. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.5.2 Other potential endogeneity concerns and attempted solutions using Entropy Balancing and treatment-effect approaches

Another potential limitation of our pseudo-panel fixed effects regression approach would be that it may not control for a possible selection bias related to the non-random nature of electrification. For instance, a household's probability to connect to electricity could be not independent of factors such as the area of residence (Urban versus Rural), the characteristics of the household and the head of the household, and the level of revenue of the household (proxied here by household expenditures). This leads us to test the robustness of our results using the most robust impact assessment approaches: entropy balancing and the treatment-effects methodologies (IPW regression adjustment, nearest-neighbor matching, and propensity-score matching).

Entropy Balancing approach:

The first approach, Entropy Balancing, is based on the idea that connection to electricity represents a treatment. Connected households constitute the treatment group, while none-connected households constitute a potential control group. The average treatment effect on treated households (ATT) is defined as follows:

$$\tau_{\text{ATT}} = E[y(1) \mid T = 1] - E[y(0) \mid T = 1] \tag{2}$$

$y(\cdot)$ is the outcome variable (biomass fuel consumption or arable farms size). T indicates whether the household is connected to electricity ($T = 1$) or not ($T = 0$). Therefore, $E[y(1) \mid T = 1]$ is the expected outcome for the connected households and $E[y(0) \mid T = 1]$ is the counterfactual outcome, i.e. the outcome that a connected household would have obtained if it had not connected to electricity. As the counterfactual outcome is not observable, we need an appropriate proxy to identify the ATT. If the treatment is randomly assigned, then the average outcome of the none-connected households, $E[y(0) \mid T = 0]$, is an appropriate proxy. However, connection to electricity could be non-random.

The idea of matching estimators is to mimic randomisation with respect to treatment assignment. The unobserved counterfactual outcome is imputed by matching treated units with untreated units that are as similar as possible with respect to all pre-treatment characteristics that: (i) are associated with selection into treatment (i.e. the probability to have access to electricity), and (ii) influence the outcome of interest. The realisations of the outcome gap measure for these matches are then used as an empirical proxy for the unobserved counterfactual. Formally, the matching-based ATT estimate is defined as follows:

$$\tau_{\text{ATT}}(x) = E[y(1) \mid T = 1, X = x] - E[y(0) \mid T = 0, X = x] \tag{3}$$

where x is a vector of relevant pre-treatment characteristics (our control variables), $E[y(1) \mid T = 1, X = x]$ is the expected outcome for the units that received the treatment, and $E[y(0) \mid T = 0, X = x]$ is the expected outcome for the best matches of the treated units.

Here, as Neuenkirch and Neumeier (2016) in the analysis of the effect of US sanctions on poverty gap in the target countries, we use Entropy Balancing to select matches for units exposed to the treatment and to estimate the ATT. Entropy Balancing is a method proposed by Hainmueller (2012). This method is implemented in two steps. First, weights are calculated and assigned to the units not subject to treatment. These weights are chosen to satisfy prespecified equilibrium constraints involving sample moments of the pre-treatment features while at the same time remaining as close as possible to the uniform base weights. In our analysis, the equilibrium constraints require equal covariate means between the treatment and control groups, which ensures that the control group contains, on average, non-treatment units that are as similar as possible to the treatment units. Second, the weights obtained in the first step are used in a regression analysis with the treatment indicator as an explanatory variable. This yields an estimate of the ATT, i.e. the conditional difference in the means of the outcome variable between the treatment group and the control group.[7] Broadly, the idea of Entropy Balancing here is to compare the outcome gap of connected households with that of none-connected households that are as similar as possible to the connected one. The average difference in biomass fuel consumption and arable farms size between the connected households and the "closest" none-connected households must then be due to the treatment, i.e. connection to electricity. In this sense, the empirical approach mimics a randomised experiment by balancing the treatment and control groups on the basis of observable characteristics.

By combining matching and regression analysis, Entropy Balancing has some advantages over other treatment effect estimators. A particularly important advantage over regression-based approaches (including DiD estimation) as well as propensity score-based matching methods is that Entropy Balancing is non-parametric in the sense that no empirical model for the outcome variable or selection into treatment needs to

[7] In the regression step, we additionally control for the covariates used in the first step. This is equivalent to including control variables in a randomised experiment to increase the efficiency of the estimation.

be specified. Furthermore, unlike regression-based analyses, there is no multicollinearity, as the reweighting scheme orthogonalizes the covariates to the treatment variable. Finally, unlike other matching methods, Entropy Balancing ensures a high balance of covariates between treatment and control groups, even in small samples.

Treatment-effects estimators (”teffect”):

We also tested the robustness of our findings by using the treatment-effects estimators (IPW regression adjustment, nearest-neighbor matching, and propensity-score matching). These estimators measure the average difference in the outcome between the connected group and the none-connected group (comparison of the outcome of the treated group with the outcome of the untreated group). These methods allow transforming electricity adoption into a quasi-experimental event, and as such estimate the treatment effect of electricity adoption on the biomass fuel consumption and the arable farms size.

The inverse-probability-weighted regression adjustment (IPWRA), the nearest-neighbor matching, and the propensity-score matching estimate the average treatment effect on the treated (connected households) from observational data.

IPWRA estimators use weighted regression coefficients to compute averages of treatment-level predicted outcomes, where the weights are the estimated inverse probabilities of treatment. The contrasts of these averages estimate the treatment effects. IPWRA estimators have the double-robust property.

Both the nearest-neighbor matching and the propensity-score matching estimate the average treatment effect on the treated from observational data and impute the missing potential outcome for each household by using an average of the outcomes of similar households that receive the other treatment level. Meanwhile, in the nearest-neighbor matching similarity between households is based on a weighted function of the covariates for each observation. In the propensity-score matching, similarity between households is based on estimated treatment probabilities, known as propensity scores. Finally, the treatment effect is computed by taking the average of the difference between the observed and imputed potential outcomes for each household in both methods.

Table 4 highlights the negative and statistically significant effect of access to electricity on firewood collection and arable farms at the household level for all our estimators, confirming our main findings.

Table 4: Robustness check – The effect of electricity access on firewood collection and arable farms

	Firewood collection				**Arable farms**			
	Entropy balancing	IPW regression adjustment	Nearest-neighbor matching	Propensity-score matching	Entropy balancing	IPW regression adjustment	Nearest-neighbor matching	Propensity-score matching
ATT	-0.659***	-0.312***	-0.276***	-0.284***	-0.417***	-0.235***	-0.201***	-0.211***
	[0.076]	[0.005]	[0.008]	[0.008]	[0.094]	[0.008]	[0.009]	[0.009]
Observations	40498	40498	40498	40498	40498	40498	40498	40498
Pseudo R^2	0.292	n.a	n.a	n.a	0.163	n.a	n.a	n.a

Notes: The table highlights the negative and statistically significant effect of access to electricity on firewood collection and arable farms. The Entropy balancing coefficients represent the average treatment effects on the treated (ATT) obtained by weighted probit regressions. Our control variables are included in the first stage and second stage and the standard errors are clustered at strates level. The treatment-effects estimation coefficients represent the average treatment effects on the treated (ATT) obtained by IPW regression adjustment, nearest-neighbor matching, and propensity-score matching. Unreported constant is included. Standard errors in brackets. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

4.6 Heterogeneity

In the first side of Table 5, we can see that the overall effect of electrification on biomass fuel consumption is mainly driven by the effect in rural areas (Rural). Indeed, the beneficial overall effect of electrification on firewood collection disappears when looking at urban areas (Urban, Intermediate cities, District of Abidjan). The non-significance of the effect in urban areas could nevertheless be explained by several factors, including an already high electricity access rate in these areas, the availability of other alternative sources (e.g. butane gas), or the considerable distance to forests. As in the first side, the second side of the table also documents that the overall effect of electrification on arable farms size is mainly driven by the effect in rural areas. The electrification significantly reduce forest loss for the sub-sample of rural households as predicted by our theoretical Framework I based on the subsistence economy. It is also the largest effect we found.

Table 5: Heterogeneity check – The effect of electricity access on firewood collection and arable farms

	Firewood collection					**Arable farms**				
	Full sample	Rural	Urban	Intermediate cities	District of Abidjan	Full sample	Rural	Urban	Intermediate cities	District of Abidjan
Electricity access rate	-0.147**	-0.181***	-0.083	0.051	-0.037	-0.265**	-0.788**	0.024	-0.144	0.006
	[0.060]	[0.058]	[0.074]	[0.169]	[0.061]	[0.106]	[0.302]	[0.035]	[0.210]	[0.008]
Male/female ratio	-0.187**	-0.352**	-0.190**	-0.552***	-0.067	-0.149	0.175	-0.197	-0.687	-0.007
	[0.075]	[0.139]	[0.078]	[0.149]	[0.087]	[0.175]	[0.657]	[0.194]	[0.730]	[0.008]
Households size	-0.011**	0.015***	-0.022***	-0.020**	-0.015**	0.005	0.024	-0.001	-0.016	0.001
	[0.005]	[0.005]	[0.006]	[0.008]	[0.006]	[0.009]	[0.033]	[0.004]	[0.014]	[0.001]
Male-headed households	-0.076	-0.086	-0.058	0.020	-0.119	0.093	-0.315	0.094	0.536	0.011**
	[0.076]	[0.079]	[0.075]	[0.157]	[0.075]	[0.067]	[0.497]	[0.066]	[0.407]	[0.004]
Refrigerator owners	0.017	-0.002	0.023	-0.492***	0.126**	-0.040	-0.016	-0.015	-0.177	0.007
	[0.035]	[0.019]	[0.048]	[0.148]	[0.048]	[0.037]	[0.069]	[0.023]	[0.213]	[0.005]
Log expenditure	0.012**	0.005	0.015**	0.049***	-0.013**	-0.141	-0.141***	-0.050	-0.123	-0.000
	[0.005]	[0.005]	[0.007]	[0.011]	[0.005]	[0.093]	[0.041]	[0.041]	[0.099]	[0.001]
Stove owners	-0.071**	-0.023	-0.101**	0.252*	-0.004	-0.012	0.097	-0.011	0.225	-0.009**
	[0.034]	[0.019]	[0.046]	[0.137]	[0.046]	[0.049]	[0.087]	[0.014]	[0.235]	[0.004]
Observations	552	184	368	184	184	552	184	368	184	184
R^2	0.131	0.264	0.173	0.446	0.269	0.016	0.207	0.024	0.056	0.097
ρ	0.897	0.229	0.445	0.287	0.221	0.284	0.173	0.332	0.333	0.234

Notes: The Table estimates the effect of electrification rate on the percentage of households collecting firewood and on average arable farms size within cohorts. The results document that the effect of electrification on the percentage of households collecting firewood and on average arable farms size is negative and statistically significant when considering the entire sample. This effect is driven primarily by rural areas. The effect is not statistically significant in urban areas. The coefficients are obtained using Within estimation taking into account cohort fixed effects (FE), which capture any time-invariant differences across cohorts. Unreported constant is included. Robust Standard errors in brackets, which permit for the errors to be heteroskedastic and also be correlated with each other within clusters. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6 highlights further important heterogeneity. It documents that electrification reduces the average arable farms size by improving the Boserup land use intensity factor (Fallow land/(Fallow land+Crop land)). This is more noticeable in the decrease in fallow land than in cultivated land.

Finally, we empirically test for the existence of a possible threshold effect of electrification. We therefore test the quadratic model (Table 7). The resolution gives us a threshold of $S = 0.795632$, i.e. an electrification rate of 80% (Figure 4). For an electrification rate below 80%, the effect of electrification would be to reduce arable farms size in Côte d'Ivoire. On the contrary, above an access rate of 80%, electrification contributes to rapid clearance of Ivorian forests for agricultural purposes. According to Figure 5, at the national level and in rural areas, the overall effect of electrification would be to reduce forest loss because electrification access rates are still well below the 80% threshold. In urban areas, the overall effect of electrification would be to increase forest loss from the 2000s onwards (urban electrification rate exceeding 80%).

Table 6: Heterogeneity check – The effect of electricity access on arable farms, Boserup factor, crop and fallow land

	Total land	Boserup factor	Crop land	Fallow land
Electricity access rate	-0.265**	-0.382***	-0.314	-0.858*
	[0.106]	[0.114]	[0.380]	[0.497]
Male/female ratio	-0.149	0.386**	-0.184	-0.501
	[0.175]	[0.193]	[0.158]	[1.145]
Households size	0.005	0.024***	-0.028	0.009
	[0.009]	[0.007]	[0.032]	[0.043]
Male-headed households	0.093	0.284**	0.486	0.001
	[0.067]	[0.128]	[0.339]	[0.477]
Refrigerator owners	-0.040	0.292***	-0.078	0.099
	[0.037]	[0.056]	[0.088]	[0.070]
Log expenditure	-0.141	-0.151*	-0.849**	-0.726
	[0.093]	[0.078]	[0.330]	[0.578]
Stove owners	-0.012	0.123**	0.049	0.075
	[0.049]	[0.058]	[0.090]	[0.133]
Observations	552	486	361	348
R^2	0.016	0.541	0.046	0.011
ρ	0.284	0.260	0.442	0.234

Notes: The table highlights some important heterogeneity. Electrification reduces the average arable farms size by improving the Boserup land use intensity factor (Fallow land/(Fallow land+Crop land)). This is more noticeable in the decrease in fallow land than in cultivated land. The coefficients are obtained using Within estimation taking into account cohort fixed effects (FE), which capture any time-invariant differences across cohorts. Unreported constant is included. Robust standards errors permit for the errors to be heteroskedastic and also be correlated with each other within clusters. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

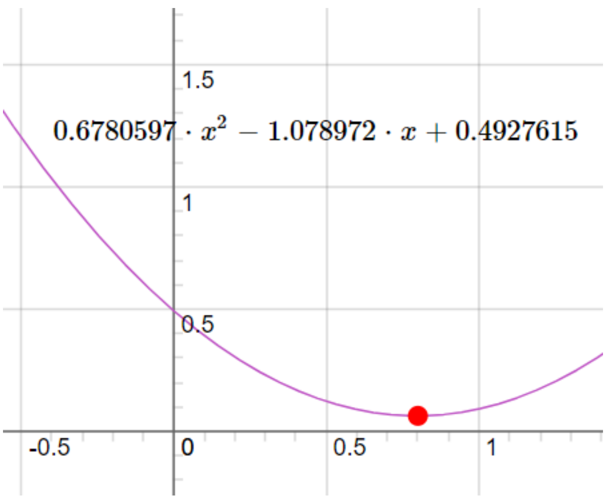

Figure 4: Threshold effect of electrification on arable farms size

Table 7: Heterogeneity check – Threshold effect of electricity access on arable farms

	FE
Electricity access rate	-1.079**
	[0.428]
Electricity access rate × Electricity access rate	0.678**
	[0.335]
Male/female ratio	-0.129
	[0.203]
Households size	0.002
	[0.014]
Male-headed households	0.088
	[0.168]
Refrigerator owners	-0.026
	[0.077]
Log expenditure	-0.128
	[0.159]
Stove owners	-0.027
	[0.078]
Observations	552
R^2	0.026
ρ	0.292

Notes: The Table documents the significance of the quadratic model. This characterizes a threshold effect of electrification on the average size of arable farms. Our calculations allow us to find a threshold of 80%, a situation that characterizes the most urbanized areas of the country. In these urban areas, there is more commercial agriculture –as opposed to food crops in remote rural areas– because households have access to national and international markets. The coefficients are obtained using Within estimation taking into account cohort fixed effects (FE), which capture any time-invariant differences across cohorts. Unreported constant is included. Robust Standard errors in brackets, which permit for the errors to be heteroskedastic and also be correlated with each other within clusters. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

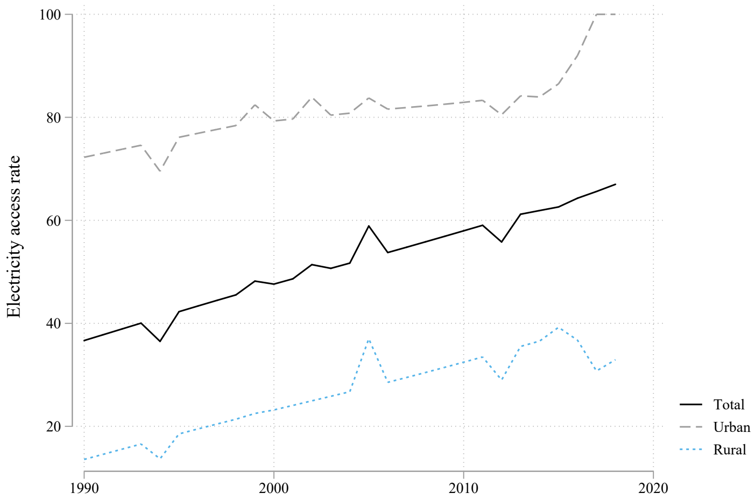

Figure 5: Electrification rate in Côte d'Ivoire between 1990 and 2018 (WDI)

5 Conclusion

The primary aim of this study was to assess the impact of electrification on forest loss caused by the activities of Ivorian households, such as firewood collection and expansion of arable farms, which are harmful to forests. We examined forest loss at the household level by looking at the percentage of households involved in firewood collection and the size of their arable farms. To address any possible endogeneity issues, we used a pseudo-panel fixed effects regression model and various alternative specifications (time FE inclusion; time trends inclusion; cocoa price trends inclusion; probit model; entropy balancing; IPW regression adjustment; nearest-neighbor matching; and propensity-score matching).

Our sample includes 138 cohorts of households over the years 1998, 2002, 2008 and 2015 in our pseudo-panel fixed effects approach, and an important number of 40,498 observations in our impact assessment analysis. Our empirical findings indicate that electrification would have a significant impact on reducing forest loss caused by the activities of Ivorian households. Specifically, a 1% increase in the electrification rate within a cohort, on average, lowers the percentage of households collecting firewood by 0.147%, and reduces the average arable farms size by 0.265%. Our results suggest that electrification could be one the solutions for reducing the part of the forest loss due households practices in Côte d'Ivoire. In other words, in addition to the positive effects on job creation and poverty reduction, Côte d'Ivoire's ongoing national electrification programs could also contribute to the preservation of the country's forests.

It is also important to point out that the decrease in firewood collection linked to electrification is more likely to result from the acquisition of equipment such as refrigerators than from the substitution of electricity for firewood as a source of energy for cooking (stove). Indeed, by acquiring refrigerators, households are better able to preserve their food, thus leading to a reduction in cooking frequency (optimization). Moreover, the electrification of rural or remote localities would have a greater environmental impact than the electrification of localities integrated into the national market (see subsistence effect vs firm effect in the theoretical framework).

As part of the main limitation of this study, we could –to a lesser extent– attribute the effects resulting from the decrease in arable farms size to those that specifically pass through the channel of agricultural productivity (or profitability). Indeed, due to a lack of information on household agricultural inputs, we have made the assumption that households with access to electricity in their living home are more likely to have access to electricity in their agricultural production process compared to non-connected households. This assumption could be "strong" in some circumstance as having electricity at home does not necessary imply having electricity on one's arable farm. Meanwhile, it should be remembered that productivity (or profitability) can also be seen as the increase in agricultural product prices in a locality following electrification. This could increase the expected future rent from the land, and thus accelerate the race for arable farms (which would result in a decrease in arable farms size or agricultural intensification).

In terms of avenues for research, we would consider possible assessments of the effects of electrification passing through the agricultural productivity channel if more accurate data are available. This would make it possible to confirm or reject Jevons' paradox and Borlaug's hypothesis we mentioned for instance. We would also consider, subject to the availability of locality variables, an analysis based on a panel of localities (districts, regions, departments, villages etc.). Finally, similar analyses focusing on other types of actors such as companies (logging, mining, oil, etc.), the public actors (road infrastructure expansion, hydroelectric dam construction, urbanization policy, etc.), or on other types of household activities (livestock rearing, gold panning, etc.) would be a considerable addition to this growing body of literature.

Declarations

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Ethics

This article does not contain any studies involving human participants performed by any of the authors.

Conflicts of interest/Competing interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Consent to participate

On behalf of all authors, the corresponding author states that all authors consent to participate.

Consent for publication

On behalf of all authors, the corresponding author states that all authors consent to publication.

Availability of data and material

Available on request.

Code availability

Available on request.

Disclaimer

The authors only are responsible for any omissions or deficiencies.

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A Theoretical framework (detailed description)

We start by recalling some key assumptions about the impact that electrification (e) could have on a number of key parameters or intermediate variables from the framework such as agricultural productivity (A), Boserup's land use intensity factor (m), off-farm employment (L^{out} or w^{out}) and demography (N). In the rest of this section, we assume that $\frac{dA}{de}$ >0. Indeed, according to Amuakwa-Mensah (2019), electrification has a positive and significant effect on productivity. Similarly, Barnes and Binswanger (1986) argue that electrification improves agricultural productivity through local communities' acquisition of electric pumps. Assunção et al. (2014) also document that rural electrification has a positive effect on productivity in Brazil. We also assume that $\frac{dm}{de}$ >0. In fact, access to electricity helps to considerably reduce the length of time land is left fallow, notably thanks to irrigation (Assunção et al., 2014). Shively and Pagiola (2004) also find that improving the irrigation system in the Philippines would have reduced forest loss by half.

We then assume that electrification is a source of new employment opportunities outside the agricultural sector or the off-farm sector ($\frac{dL^{out}}{de}$ >0 and $\frac{dw^{out}}{de}$ >0). Indeed, according to Chhay et al. (2020), access to electricity has increased non-agricultural self-employment in Cambodia. For Akpandjar and Kitchens (2017), access to electricity in Ghana led to a shift away from agriculture to higher-skilled wage-earning employment. In the same vein, Dinkelman (2011) points out that rural electrification promotes off-farm employment and accelerates the creation of off-farm micro-enterprises. Tagliapietra et al. (2020) conclude that access to electricity would induce the migration of agricultural labor to non-agricultural sectors and increase the proportion of workers in households. Finally, it can be assumed that electrification has an ambiguous effect on demography ($\frac{dN}{de}$ <>0). In fact, as electrification is one of the factors in the development of a locality, an electrified locality should attract more people than a similar, non-electrified locality. Thanks to migration, electrification would increase demography. However, this positive effect of electricity on demography becomes questionable if one focuses on fertility. Indeed, Harbison and Robinson (1985) document that, based on a comparison of nine studies conducted in six countries, rural electrification reduces fertility rates. However, Peters and Vance (2011) find that the effect of electrification would be to increase fertility in urban areas and to reduce it in rural areas.

A.1 Framework I: Subsistence economy (no labor market)

In this kind of economy, found in rural areas of Côte d'Ivoire, households are assumed to have no access to markets (or are very distant from international and national markets). Households produce essentially for their own consumption (self-sufficiency). Households maximize their leisure time under the constraint of reaching a certain level of production ($\overline{Q}^{ag} = C^{min}$) necessary for their subsistence. They therefore extend their cultivated area H until they reach the required production level $\overline{Q}^{ag}$. On the basis of Von Thünen (1966)'s centre-periphery framework, we assume that land is abundant and homogeneous. We also assume that the village population is concentrated in the centre of the village. Assuming that the number of households is N, the total agricultural land area would be a circle around the village:

$$N \cdot H = \pi(r^{max})^2 = \int_0^{r^{max}} (2\pi r)dr \tag{A.1}$$

where r represents the village-field distance and r^{max} represents the agricultural frontier.

We can also introduce Boserup (1965)'s land-use intensity factor (m) to take account of the length of cropping (C) and fallow (F) periods. Boserup defined this land-use intensity as $m = \frac{C}{C+F}$. The land under cultivation by the representative household is thus given by:

$$H = \frac{m\pi}{N}(r^{max})^2 = \int_0^{r^{max}} \frac{2m\pi r}{N} dr \tag{A.2}$$

Let us now express the agricultural frontier in terms of the subsistence threshold (or requirement):

$$\overline{Q}^{ag} = A \cdot H = A\frac{m\pi}{N}(r^{max})^2 \tag{A.3}$$

$$r^{max} = \sqrt{\frac{N\overline{Q}^{ag}}{\pi m A}} \tag{A.4}$$

From Equation A.4 it can be deduced that in a subsistence economy, the frontier of agriculture (or forest loss) is determined by the following factors: demography (N), subsistence level (C^{min}), land-use intensity (m) and, mainly, agricultural productivity (A).

Now, let $r^{max} = f\big(N,m,A\big)$ be a multivariate function and $N(e)$, $m(e)$, $A(e)$ be functions of e. If it exists, the total derivative with respect to e of the composite function $f\Big(N(e),m(e),A(e)\Big)$ is derived from the differential expression:

$$\frac{df}{de} = \frac{dr^{max}}{de} = \underbrace{\frac{\partial r^{max}}{\partial N} \times \frac{dN}{de}}_{\frac{dr^{max}}{de}\big|_N} + \underbrace{\frac{\partial r^{max}}{\partial m} \times \frac{dm}{de}}_{\frac{dr^{max}}{de}\big|_m} + \underbrace{\frac{\partial r^{max}}{\partial A} \times \frac{dA}{de}}_{\frac{dr^{max}}{de}\big|_A} \tag{A.5}$$

with, for the rest of this paper, $\frac{dr^{max}}{de}\Big|_X$ meaning the effect of electrification (e) on forest loss (r^{max}) via a given channel X (N, m, A, etc.). Equation A.4 gives us:

$$\frac{\partial r^{max}}{\partial N} = \frac{r^{max}}{2N} > 0 \Leftrightarrow \boxed{\frac{dr^{max}}{de}\Big|_N = \frac{r^{max}}{2N} \times \frac{dN}{de} > 0} \text{ if } \frac{dN}{de} > 0 \tag{A.6}$$

If the migratory effect resulting from electrification outweighs the natality effect, then the effect of electrification would be to increase forest loss through demography (Equation A.6). On the other hand, if the natality or fertility effect is much greater than the migratory effect, then in this case, electrification of a locality would have a mitigating effect on the agricultural frontier, and thus on forest loss.

$$\frac{\partial r^{max}}{\partial A} = -\frac{r^{max}}{2A} < 0 \Leftrightarrow \boxed{\frac{dr^{max}}{de}\Big|_A = -\frac{r^{max}}{2A} \times \frac{dA}{de} < 0} \tag{A.7}$$

Based on the hypothesis (already justified at the beginning of the theoretical framework) that access to electricity promotes agricultural productivity or agricultural yield per unit area ($\frac{dA}{de} > 0$) via, for example, drilling of boreholes or the adoption of irrigation techniques, then electricity would act as a mitigating factor on the agricultural frontier (or forest loss) through agricultural productivity (Equation A.7).

$$\frac{\partial r^{max}}{\partial m} = -\frac{r^{max}}{2m} < 0 \Leftrightarrow \boxed{\frac{dr^{max}}{de}\Big|_m = -\frac{r^{max}}{2m} \times \frac{dm}{de} < 0} \tag{A.8}$$

Assuming also that electricity, notably through the implementation of irrigation, drilling of boreholes and electric pumping techniques, reduces fallow time (the value of m increases), we can state that electrification reduces the agricultural frontier, and therefore its effect would be to reduce forest loss (Equation A.8).

Finally, it can also be imagined that a high subsistence threshold ($\overline{Q}^{ag}$) would require the collection of more firewood, and therefore more forest loss. The greater households' food requirements, the more they clear forest for agricultural purposes and the more firewood they collect, the higher the forest loss rate would be.

A.2 Framework II: Chayanovian economy (imperfect labor market)

This type of economy refers to intermediate cities in terms of development in the case of Côte d'Ivoire, or urban areas distant from Abidjan (the economic capital). Within these cities, we find both a subsistence economy and a market economy (farm firm economy).[8] In this kind of economy, a representative household maximizes its utility (U) by finding a trade-off between consumption (C) and leisure time (T). It is generally assumed that there is no perfect labor market. That is, a household may sell some of its labor on the labor market (off-farm), but only family labor is allowed on agricultural plantations. The household maximization program is written:

$$\max_{r^{max}} U(C,T) \equiv \max_{r^{max}} U\left(A \cdot \int_0^{r^{max}} \frac{2m\pi r}{N} dr + w^{out} L^{out}, \int_0^{r^{max}} (1+c\cdot r)\frac{2m\pi r}{N} dr + L^{out}\right) \tag{A.9}$$

with the on-field labor (clearing, weeding, harvesting, etc.) cost set to 1 and $c \cdot r$ representing the cost due to both the forest monitoring intensity (c) and the agricultural land expansion to the detriment of forest around a given locality (r). This cost include above all the risk of being caught for illegal occupation of a forest and increases with the level of electrification in the locality and with the farm's distance from the center the locality. The idea is that electrification as a convenience would increase the presence of "water and forestry" agents. The task of these agents is to limit the advance of the agricultural frontier to the detriment of the forest. At the optimum, we have:

$$\frac{\partial U}{\partial r^{max}} = \frac{\partial U}{\partial C} \times \frac{\partial C}{\partial r^{max}} + \frac{\partial U}{\partial T} \times \frac{\partial T}{\partial r^{max}} = 0 \tag{A.10}$$

$$U_C \times \left(A \cdot \frac{2m\pi}{N} r^{max}\right) + U_T \times \left((1+c\cdot r^{max})\frac{2m\pi}{N} r^{max}\right) = 0 \tag{A.11}$$

$$A = -\frac{U_T}{U_C} \times (1+c\cdot r^{max}) \tag{A.12}$$

At the optimum, the productivity resulting from clearing an additional unit of land for agricultural purposes (A) is equal to the cost required at the agricultural frontier $(1+c\cdot r^{max})$, multiplied by the opportunity cost of labor ($-\frac{U_T}{U_C}$).

$$r^{max} = \frac{1}{c} \times \left(\frac{A}{-\frac{U_T}{U_C}} - 1\right) \tag{A.13}$$

[8] See Angelsen (1999) for more details on the Chayanovian economy.

The agricultural frontier depends on agricultural productivity A (or crop unit value per hectare, since the price of agricultural output is taken as cash and is therefore worth one), cost c and the opportunity cost of labor $\left(-\frac{U_T}{U_C}\right)$. $-\frac{U_T}{U_C}$ represents the Marginal Rate of Substitution (MRS) between consumption and leisure, i.e. the amount of consumption that a household is willing to renounce for one unit of extra leisure time. It should be noted that this figure becomes very small when consumption is fairly close to the subsistence level and very large when leisure time is close to zero.

However, $-\frac{U_T}{U_C}$ is endogenous because it also depends on r^{max}, so the effect of other quantities on r^{max} cannot be interpreted very well. To provide more relevant comparative analyses, Angelsen (1999) introduces a function which is a combination of the standard multiplicative Stone-Geary utility function and the Houthakker additive function:

$$U(C,T) = (C - C^{min})^{\alpha} + v(T^{max} - T)^{\beta} \text{ with } v > 0;\ \alpha, \beta \in (0,1); (C - C^{min}) > 0;\ (T^{max} - T) > 0 \quad \text{(A.14)}$$

Moreover, when we set $\alpha = \beta$, we find ourselves with the CES (Constant Elasticity of Substitution) production function. This function makes it possible, above all, to distinguish the case where the household behaves as a producer, maximising its agricultural profit, from the case where the household behaves as a consumption unit maximising its utility. For more details on this function, refer to Angelsen (1999). Consequently, the partial derivatives of the new function are:

$$U_C = \alpha(C - C^{min})^{\alpha-1} \quad \text{and} \quad U_T = -\beta v(T^{max} - T)^{\beta-1} \quad \text{(A.15)}$$

From this, we can deduce the expression for the MRS between consumption and leisure:

$$z \equiv -\frac{U_T}{U_C} = \frac{v\beta(C - C^{min})^{1-\alpha}}{\alpha(T^{max} - T)^{1-\beta}} \quad \text{(A.16)}$$

The impact of electrification on forest loss through productivity is derived from this:

$$\left.\frac{dr^{max}}{de}\right|_A = \frac{1}{\mu} \times \left[1 - \frac{\partial z}{\partial A} \times \frac{A}{z}\right] \times \frac{dA}{de} \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_A < 0} \Leftrightarrow Y < \frac{C^{min} - w^{out}L^{out}}{\alpha} \quad \text{(A.17)}$$

When the production value Y is below $(C^{min} - w^{out}L^{out})/\alpha$, then the subsistence effect would predominate over the farm-firm effect (Equation A.17). In this case, electrification would have a mitigating effect on the agricultural frontier, and thus on forest loss, through productivity. It should be remembered, however, that in the richer localities of the country, households behave more like firms that maximize their profit, since the question of subsistence is rarely raised in these cases. This result therefore remains more relevant in the case of the country's poor localities. The increase in agricultural productivity due to electrification would therefore not have the same effects on the agricultural frontier in poor and rich localities in Côte d'Ivoire. Rural electrification programs would therefore help to reduce forest loss and therefore they can be environmentally sustainable. Finally, it is important to note that the farm-firm effect would always dominate when the off-farm income is higher than the subsistence requirement $(C^{min} < w^{out}L^{out})$. Then a low value of α means that the valuation of consumption above subsistence declines rapidly. This is especially the case in societies with low materialism where an increase in agricultural productivity due to electrification would have the effect of reducing the amount of cultivated land because more importance is given to leisure.

The other interesting result remains the analysis of the impact of electrification on the agricultural frontier through costs (Equation A.18 below). Costs c include above all the risk of being caught for illegal occupation of a forest area. Our intuition is that the risk of being caught increases with greater presence of ”water & forest” agents in a locality. As these agents are Ivoirian government officials, they are essentially posted to localities with a certain number of amenities, including access to electricity. Forests in electrified localities therefore benefit from more surveillance due to the increased presence of these agents, and therefore more risk for operators who extend their cultivated area. We therefore assume that $\frac{dc}{de} > 0$.

$$\left.\frac{dr^{max}}{de}\right|_c = -\frac{1}{\mu} \times \left[z \cdot r^{max} + \frac{\partial z}{\partial c} \times (1 + c \cdot r^{max}) \right] \times \frac{dc}{de} < 0 \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_c < 0} \tag{A.18}$$

Regardless of the effect that prevails (subsistence effect vs farm-firm effect), electrification has a mitigating effect on forest loss through, among other things, increased monitoring frequency. Indeed, in localities benefiting from electricity, there is genuine control over forests, so it is more expensive to expand arable farms size to the detriment of the forest than in other localities.

$$\text{Since} \quad \frac{\partial z}{\partial h} = z_C \cdot \int_0^{r^{max}} A \cdot r dr + z_T \cdot \int_0^{r^{max}} (1 + c \cdot r) r dr > 0 \quad \text{and} \quad h = \frac{2\pi m}{N}$$

Equation A.19 and Equation A.20 then tell us that the impact of electrification on the agricultural frontier, whether through demography or the adoption of intensive agriculture, does not depend on the dominance of any one effect (subsistence or farm-firm). The effects are also the same as those found in Framework I.

$$\left.\frac{dr^{max}}{de}\right|_m = -\frac{1}{\mu} \left[\frac{\partial z}{\partial h} \times (1 + c \cdot r^{max}) \right] \times \frac{dm}{de} \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_m < 0} \tag{A.19}$$

Indeed, electrification has a mitigating effect on forest loss when it reduces the fallow period on arable farms (Equation A.19).

$$\left.\frac{dr^{max}}{de}\right|_N = -\frac{1}{\mu} \left[\frac{\partial z}{\partial h} \times (1 + c \cdot r^{max}) \right] \times \frac{dN}{de} \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_N > 0} \text{ if } \frac{\partial N}{\partial e} > 0 \tag{A.20}$$

The effect involving demography, on the other hand, remains ambiguous because it depends on two further, opposing effects, namely migration and natality (Equation A.20).

Finally, we mention the effect of electrification on the agricultural frontier through the channel of employment opportunities outside the agricultural sector (off-farm sector).

$$\left.\frac{dr^{max}}{de}\right|_{L^{out}} = -\frac{1}{\mu} \times \left[\frac{\partial z}{\partial L^{out}} \times (1 + c \cdot r^{max}) \right] \times \frac{dL^{out}}{de} \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_{L^{out}} < 0} \text{since } \frac{\partial z}{\partial L^{out}} = w \cdot z_C + z_T > 0 \tag{A.21}$$

One of the major objectives of electrification programs remains the creation of employment opportunities in order to eradicate extreme poverty in rural areas. Electrification at the locality level offers huge employment opportunities outside the agricultural sector. It would therefore make agricultural labor available to the new sectors that have emerged thanks to the arrival of electricity. Through the complementarity of factors, this can slow forest clearance at the expense of agriculture (Equation A.21).

$$\left.\frac{dr^{max}}{de}\right|_{w^{out}} = -\frac{1}{\mu} \times \left[\frac{\partial z}{\partial w^{out}} \times (1 + c \cdot r^{max}) \right] \times \frac{dw^{out}}{de} \Rightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_{w^{out}} < 0} \text{since } \frac{\partial z}{\partial w^{out}} = E \cdot z_C > 0 \tag{A.22}$$

This is all the more true if w^{out} (off-farm) wages are more attractive (Equation A.22). Remember that in this framework, a household cannot hire outside labor for farms work. In a country like Côte d'Ivoire, the most important channel would be self-employment (hairdressing salon, sewing, night activity, games room, video club, etc.).

A.3 Framework III: Open economy with perfect labor market (static open access)

This type of economy refers to the main cities of Côte d'Ivoire, District of Abidjan and urban areas around this District. In these areas, we assume that households have access to both national and international markets, and that the markets are fairly well integrated. In this context, increasing international agricultural commodity prices for instance could create pressure on forests (Harding et al., 2021). The market economy therefore largely prevails over the subsistence economy (disappearance of the subsistence effect in favor of the farm-firm effect). Next, the notion of static open access, as opposed to the notion of dynamic open access (following framework), refers to the fact that the clearing of forest for agricultural purposes does not give rise to a permanent property rights over the cleared area. Thus, households' rent calculation does not take into account future land yields. Moreover, unlike the previous framework, this time we introduce a perfect labor market. The wage rate for the whole economy is therefore w, thanks to the free movement of the labor force between all sectors of the economy, or at least regionally. At this rate, any household can sell or hire a labor force. The agricultural production problem can be formulated as:

$$\max_{r^{max}} R = Y - wL = A \cdot \int_0^{r^{max}} \frac{2m\pi r}{N} dr - w \int_0^{r^{max}} (1 + c \cdot r) \frac{2m\pi r}{N} dr \tag{A.23}$$

R and Y represent the farms rent and the value of agricultural production, respectively. At the optimum:

$$A = w(1 + c \cdot r^{max}) \tag{A.24}$$

$$r^{max} = \frac{1}{c} \times \left(\frac{A}{w} - 1\right) \tag{A.25}$$

We deduce that demography (N) is no longer a key channel through which electrification could influence the agricultural frontier, and thus forest loss, precisely because of the labor force migration that is allowed in this type of economy. The key channels therefore include agricultural productivity, the rate of labor remuneration and the costs of access to the forest.

$$\frac{\partial r^{max}}{\partial A} = \frac{1}{w \cdot c} = \frac{r^{max}}{A - w} > 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_A = \frac{r^{max}}{A - w} \times \frac{dA}{de} > 0} \tag{A.26}$$

Contrary to the first two frameworks, in this type of economy, the farm-firm effect always prevails. Therefore, households would globally behave like firms that maximize their agricultural profits. Electrification, by improving agricultural productivity, would lead to the expansion of the agricultural frontier, and thus to forest loss (Equation A.26). For economies that are already integrated, any policy that aims to improve agricultural productivity would lead to increased forest loss since the agricultural frontier, which was not profitable before the policy, becomes profitable after the policy is implemented.

$$\frac{\partial r^{max}}{\partial w} = -\frac{A}{c \cdot w^2} = -\frac{1+c \cdot r^{max}}{c \cdot w} < 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_w = -\frac{1+c \cdot r^{max}}{c \cdot w} \times \frac{dw}{de} < 0} \tag{A.27}$$

In this framework, it is assumed that there is free movement of labor between different sectors, giving $w^{ag} = w^{out} = w$. By creating new opportunities, electrification would boost the demand for labor, thus pushing up wage rates. As rates equalize due to the free movement of labor, this would result in higher agricultural sector wages, thus a decrease in the agricultural labor force and less agricultural pressure on forests. Broadly speaking, therefore, in this case electrification would be a means of fighting forest loss, in particular by creating off-farm employment (Equation A.27).

$$\frac{\partial r^{max}}{\partial c} = -\frac{A-w}{w \cdot c^2} = -\frac{r^{max}}{c} < 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_c = -\frac{r^{max}}{c} \times \frac{dc}{de} < 0} \tag{A.28}$$

Finally, in this kind of economy, as in the two previous frameworks, the intensity of the presence of ”water & forest” agents following electrification has a mitigating effect on forest clearance (Equation A.28).

A.4 Framework IV: Open economy with perfect labor market (dynamic open access)

This framework is just an extension of the previous one where households incorporate the dynamic nature of the agricultural rent. Households push the frontier of agriculture to the point where the discounted rent cancels out. The dynamic problem is written as follows:

$$\int_0^{\infty} e^{-\lambda t} e^{-\delta t} \left[e^{gt} A - w(1+c \cdot r^{max}) \right] dt = \int_0^{\infty} \left(\frac{A}{e^{(\delta+\lambda-g)t}} - \frac{w(1+c \cdot r^{max})}{e^{(\delta+\lambda)t}} \right) dt = 0 \tag{A.29}$$

with λ being the probability of losing the area cleared in each period, δ is the discount rate or rate of preference for the present and g is the rate of growth in agricultural commodity prices or agricultural output that households expect.

$$\int_0^{\infty} e^{-\lambda t} e^{-\delta t} \left[e^{gt} A - w(1+c \cdot r^{max}) \right] dt = \frac{A}{\delta+\lambda-g} - \frac{w(1+c \cdot r^{max})}{\delta+\lambda} = 0 \tag{A.30}$$

$$r^{max} = \frac{1}{c} \times \left(\frac{\theta A}{w} - 1 \right) \text{with } \theta \equiv \frac{\delta+\lambda}{\delta+\lambda-g} > 1 \text{for } (g>0) \text{ and } (\delta+\lambda>g) \tag{A.31}$$

Since the factor θ is greater than 1 for g >0, the effect of electrification on the forest, through agricultural productivity, would be greater than the effect found in the previous static framework (Equation A.31 and Equation A.32). This is certainly due to the fact that households clear the forest even when the present rent is below zero, as they hope for a future rent. They therefore engage in forest clearance in order to establish property rights and to avoid land being taken by others.

$$\frac{\partial r^{max}}{\partial A} = \frac{\theta}{w \cdot c} = \frac{\theta r^{max}}{\theta A - w} > 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_A = \frac{\theta r^{max}}{\theta A - w} \times \frac{dA}{de} > 0} \tag{A.32}$$

If it is assumed that electrification increases the expectation of a future land rent, then it would be a vector for forest loss, particularly through the g factor. So the implementation of rural electrification programs would accelerate forest loss when we have this type of property regime. Similarly, electrification programs may increase the value given to future rent (decrease in the δ parameter), which would be to increase forest loss. Finally, it should be remembered that changes in the λ parameter depend purely on institutional factors, and therefore on the property regime. If this parameter is low, it reflects secure property rights to the land, which would be paradoxically to increase forest loss (Equation A.33). Liscow (2013) has also found this similar paradoxical result in the case of Nicaragua. He found that property rights significantly increase forest loss in the country as they increase investment, increasing agricultural productivity and therefore the returns to forest loss. For instance, titling land may exacerbate forest loss. Property rights is not a complete panacea for the environmental conservation.

$$\frac{\partial r^{max}}{\partial(\delta+\lambda)} = -\frac{\theta A}{c \cdot w} \times \frac{g}{(\delta+\lambda-g)} < 0 \text{ and } \frac{\partial r^{max}}{\partial g} = \frac{A}{c \cdot w} \times \frac{\delta+\lambda}{(\delta+\lambda-g)^2} > 0 \tag{A.33}$$

On the other hand, the effects of electrification on the agricultural frontier through access costs and opportunities remain the same as those found in the previous static framework (Equation A.34 and Equation A.35).

$$\frac{\partial r^{max}}{\partial c} = -\frac{\theta A - w}{w \cdot c^2} = -\frac{r^{max}}{c} < 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_c = -\frac{r^{max}}{c} \times \frac{dc}{de} < 0} \tag{A.34}$$

Indeed, electrification would reduce forest loss through the employment opportunities or access costs channels.

$$\frac{\partial r^{max}}{\partial w} = -\frac{\theta A}{c \cdot w^2} = -\frac{1+c \cdot r^{max}}{w \cdot c} < 0 \Leftrightarrow \boxed{\left.\frac{dr^{max}}{de}\right|_w = -\frac{1+c \cdot r^{max}}{w \cdot c} \times \frac{dw}{de} < 0} \tag{A.35}$$

A.5 Empirical discussion of each framework

This empirical discussion of our theoretical frameworks is essentially based on the heterogeneity found in the second side of our Table 5 in the paper.

· In order to check the results for Framework I (subsistence economy), we considered the sub-sample of rural households alone, on the assumption that this type of household is on average very far from markets and would therefore be more likely to fit in with the reality of a subsistence economy. Framework I tells us that if the migratory effect does not outweigh the fertility or natality effect ($\frac{dN}{de} < 0$ or $\frac{dN}{de} = 0$), then the overall effect of electrification would be to reduce forest loss ($\frac{dr^{max}}{de} < 0$). This means that the effect of electricity on forest loss (approximated here by arable farms size) would be larger for the sub-sample of rural households compared to the full sample or to the other samples in urban areas. This effect of electrification would be to significantly reduce forest loss for the sub-sample of rural households as predicted by our theoretical Framework I based on the subsistence economy. It is also the largest effect.

· Framework II can be empirically verified at two levels. First, we consider the sub-sample of intermediate cities (far from the economic capital, Abidjan) as being that which best groups together households living in a subsistence economy and those behaving as agricultural firms. The effect of electrification would be to reduce forest loss, but not statistically significant enough for this sub-sample. This is certainly linked to the fact that two effects working in opposite directions (subsistence and farm-firm effects) counterbalance one another. The second level of verification of Framework II consists of classifying the sub-samples according to their degree of market integration and comparing the effects obtained. Using the hypothesis that the effect of electrification would be to reduce forest loss and that this effect is greater for subsistence economies (result from Framework II), this effect of electrification on forest loss should increase as one moves from the most urbanized areas to the most rural areas (the effect should decrease in parallel with the rate of urbanization). Considering the Rural sample to the District of Abidjan sample, the highest negative effect is indeed found for rural areas (-0.788), followed by the intermediate cities (-0.144). For the Urban sample and the District of Abidjan, the negative effect has disappeared.[9] Thus, in a market economy, electrification programs would have smaller environmental effects compared to the effects obtained in a rural or subsistence economy.

· In Frameworks III and IV, the subsistence effect disappears with the introduction of perfect markets. The sub-sample of households living in the District of Abidjan is therefore most likely to fit this reality. In these two Frameworks, the effect of electrification would be to increase forest loss through the channel of agricultural productivity. If the global effect of electrification on forest loss is to increase forest loss in this case, then we conclude that the effect through the agricultural productivity channel outweighs, in absolute value, the combined effect through both the intensification of forest monitoring and the creation of new employment sectors that are less forest loss-intensive compared to the agricultural sector.[10] According to the results of the estimation on the District of Abidjan sample, these two opposing effects would tend to cancel each other out, although it should be noted that the effect passing through the channel of agricultural productivity (resulting from the dominance of the farm-firm effect in these types of economy) barely outweighs the mitigating effects through both the intensification of forest monitoring and the creation of new employment sectors that are less forest loss-intensive compared to the agricultural sector. So in a market economy, agricultural households behave like firms. The pro-environmental effects of electrification (strong presence of forestry authorities, creation of new opportunities outside the agricultural sector etc.) are generally outweighed by the farm-firm effect. In fact, electrification, by making it possible to improve agricultural rent, would encourage increasingly rapid forest clearance for agricultural purposes. This dynamic is even more harmful if households acquire ownership of cleared forest arable farms (open access dynamics). Indeed, we emphasize that in open access dynamics households clear the forest even when the present rent is below zero, because they hope for a future rent. They therefore clear the forest in order to establish property rights and to avoid having all the land taken. If it is assumed that electrification increases the expectation of a future land rent (increase in prices and/or in yields), then it would be a vector for forest loss, notably thanks to the future profitability anticipated by the agents. So the implementation of rural electrification programs when we have this type of property regime would reduce the intensity of land use. Basically, farmers would start clearing more land than they need at present.

To sum up, the theoretical analysis of the effect of electrification on forest loss through the agricultural productivity channel using the four frameworks gives rise to differences in terms of the amplitude or sign of the expected effects. Indeed, all other things being equal, the effect of electrification would be to reduce forest loss through the agricultural productivity channel in the absence of markets (Framework I, subsistence economy). Using the hypothesis of imperfect markets (Framework II), the effect of electrification would be to reduce forest loss when the subsistence effect prevails over the farm-firm effect, and to increase it otherwise. As soon as perfect markets are introduced (Frameworks III and IV), the effect of electrification would be to increase forest loss through the agricultural productivity channel.

[9] As noted earlier, rural households would be more likely to be subsistence households as they are further from markets.

[10] Mining and livestock farming, for instance, are more forest loss-intensive than the agricultural sector.

B Descriptive statistics

Table B1: Descriptive statistics, data from LSMS (ENV) 1998, 2002, 2008 and 2015

Variable	Year	Sample size	Mean	Std. Dev.	Min. Value	Max. Value
Access to electricity (1=yes, 0=no)	1998	4,200	0.47	0.45	0.00	1.00
	2002	10,799	0.51	0.50	0.00	1.00
	2008	12,600	0.60	0.53	0.00	1.00
	2015	12,899	0.65	0.58	0.00	1.00
Household size	1998	4,200	5.77	4.01	1.00	34.00
	2002	10,799	5.32	3.77	1.00	40.00
	2008	12,600	4.84	3.46	1.00	37.00
	2015	12,899	3.55	2.37	1.00	36.00
Firewood collection (1=yes, 0=no)	1998	4,200	0.53	0.50	0.00	1.00
	2002	10,799	0.51	0.50	0.00	1.00
	2008	12,600	0.50	0.50	0.00	1.00
	2015	12,899	0.48	0.50	0.00	1.00
Arable farm size (ha)	1998	4,200	5.64	9.26	0.00	95.00
	2002	10,799	4.53	1.85	0.00	95.00
	2008	12,600	4.10	2.29	0.00	95.00
	2015	12,899	3.42	7.55	0.00	95.00
Male/Female ratio	1998	4,200	0.52	0.50	0.00	1.00
	2002	10,799	0.54	0.50	0.00	1.00
	2008	12,600	0.55	0.50	0.00	1.00
	2015	12,899	0.56	0.31	0.00	1.00
Refrigerator ownership (1=yes, 0=no)	1998	4,200	0.16	0.37	0.00	1.00
	2002	10,799	0.12	0.33	0.00	1.00
	2008	12,600	0.25	0.16	0.00	1.00
	2015	12,899	0.28	0.26	0.00	1.00
Stove ownership (1=yes, 0=no)	1998	4,200	0.12	0.33	0.00	1.00
	2002	10,799	0.14	0.35	0.00	1.00
	2008	12,600	0.13	0.11	0.00	1.00
	2015	12,899	0.19	0.28	0.00	1.00
Per capita household consumption (euros)	1998	4,200	411.75	342.18	17.71	6,074.73
	2002	10,799	548.74	1,690.23	16.84	27,370.39
	2008	12,600	522.49	614.25	19.36	20,675.48
	2015	12,899	588.78	659.90	6.15	16,333.17
Gender of household head (1=male, 0=female)	1998	4,200	0.80	0.39	0.00	1.00
	2002	10,799	0.81	0.39	0.00	1.00
	2008	12,600	0.80	0.40	0.00	1.00
	2015	12,899	0.80	0.40	0.00	1.00
Age of household head	1998	4,200	45.94	16.89	16.00	99.00
	2002	10,799	46.33	22.81	11.00	99.00
	2008	12,600	45.51	18.80	14.00	99.00
	2015	12,899	42.84	18.93	12.00	99.00
Household living in rural area (1=yes, 0=no)	1998	4,200	0.55	0.50	0.00	1.00
	2002	10,799	0.57	0.50	0.00	1.00
	2008	12,600	0.59	0.49	0.00	1.00
	2015	12,899	0.50	0.50	0.00	1.00

C Stylized facts (continuation)

(a) Firewood collection **(b) Arable farms**

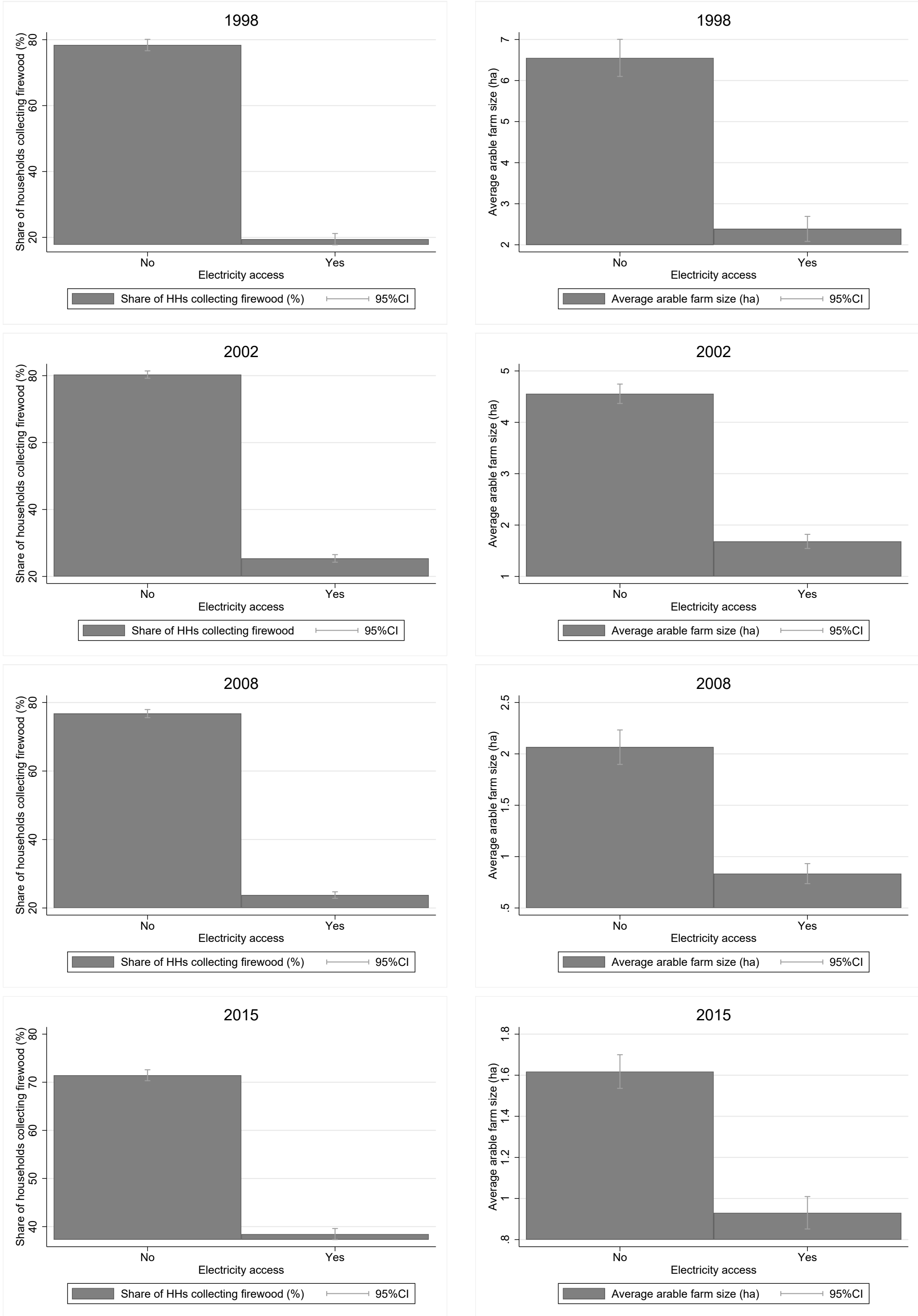

Figure C1: Connected versus non-Connected households (Yearly samples)

D Overlap

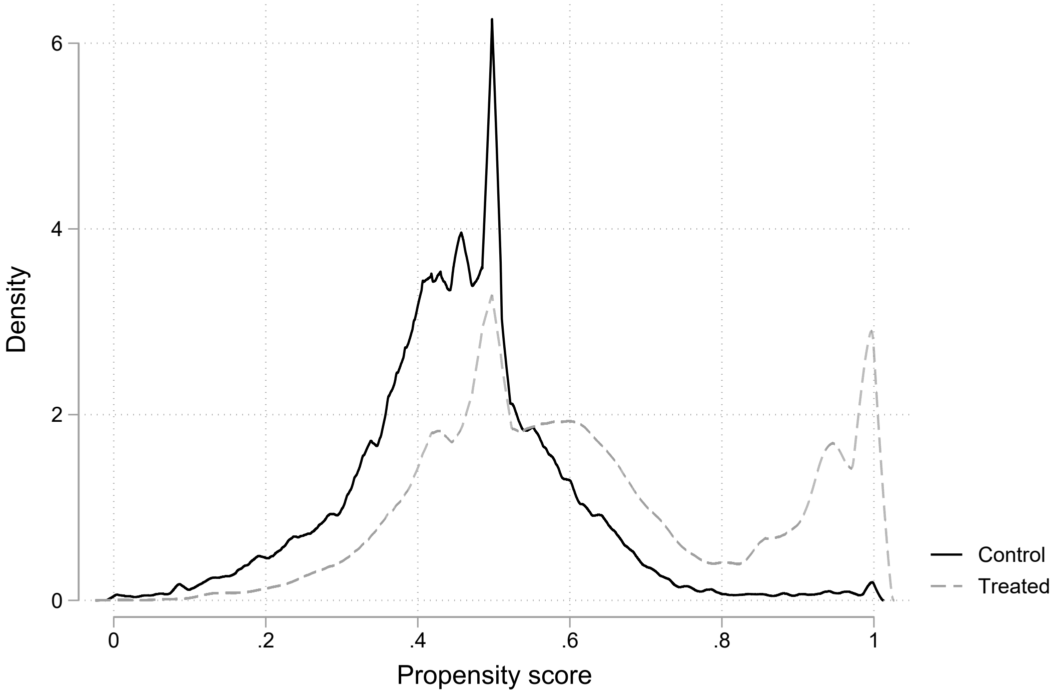

Figure D1: Connected versus non-Connected households (Overlap)