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Energy Efficiency and Local Rebound Effects: Theory and Experimental Evidence from Rwanda

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Energy Efficiency and Local Rebound Effects: Theory and Experimental Evidence from Rwanda

Abstract

Energy efficiency is a key component of climate policy. We study micro and macro rebound effects after the introduction of energy-efficient biomass cookstoves (EEBCs). We develop a model of biomass supply and demand in rural Africa. The impact of EEBCs is empirically explored in Rwanda where we randomly varied subsidy levels for EEBCs at the village-level. Demand is price elastic, so we exploit exogenous saturation variation to study local rebound effects. While adoption of EEBCs reduces household firewood consumption, we find no meaningful local rebound effects and identify conditions under which this finding generalizes to other settings – or not.

JEL-Code: R13, D12, O13, Q28

Keywords: Energy efficiency; macro-rebound effect; technology adoption; improved cooking

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1 Anicet Munyehirwe, IB&C Rwanda; Jörg Peters, RWI and University of Passau; Maximiliane Sievert, RWI Erwin Bulte, Wageningen University; Nathan Fiala, University of Connecticut. - Ordering of authors is randomized. *- Participants at the Environment for Development (EfD) Annual Meeting in Bogota, and the European Association for Environmental and Resource Economics (EAERE) conference in Manchester provided valuable comments as well as workshop and seminar participants at Frankfurt School of Finance & Management and University of Heidelberg. We also thank Gunther Bensch and Michael Grimm for feedback and comments. Data collection underlying this research was financially supported by a special grant (Sondertatbestand) from the German Federal Ministry for Economic Affairs and Energy and the Ministry of Innovation, Science, and Research of the State of North Rhine-Westphalia. Peters acknowledges funding from the German Federal Ministry of Education and Research (BMBF), funding code 011A1807A (DECADE). We thank REG/EDCL and the Ministry of Infrastructure of Rwanda for their cooperation in implementing the study. AEA RCT Registry AEARCTR-0002794.* *– All correspondence to: Maximiliane Sievert, RWI, Hohenzollernstr. 1/3, 45128 Essen, Germany, e-mail: sievert@rwi-essen.de*

1. Introduction

Increasing energy efficiency is crucial to reach global climate goals. The sustainable development agenda aims to "double the global rate of improvement in energy efficiency by 2030"(UN 2015, p.19). Policies to incentivize energy efficiency are commonly seen as win-win strategies because they foster privately profitable investments and generate environmental benefits. A broadly held view is that the energy efficiency gap offers low-hanging fruits for abating carbon emissions (Gerarden et al. 2017). However, empirical assessments suggest that closing the energy efficiency gap yields smaller gains than hypothesized (Alcott and Greenstone 2012, Fowlie et al. 2018). The rebound effect provides one possible explanation—improved energy efficiency changes the (relative) price of energy, which triggers additional consumption that nullifies some of the earlier savings (Gillingham et al. 2016).

The literature distinguishes between micro- and macro-rebounds; the former occurs if individuals increase energy consumption following an increase in efficiency, and the latter occurs typically due to price changes in the general equilibrium (Chan and Gillingham 2015). Macro-rebound effects are more difficult to identify and measure than micro-rebounds,[1] and have not been studied empirically (Gillingham et al. 2016). Our innovation is to study macro rebound effects at the local village market level empirically by inducing exogenous variation in the saturation of a new technology at the village level.

One prominent domain to study improvements in energy efficiency is the use of biomass for cooking – the dominant primary energy source in much of the Global South, accounting for more than 75% of total primary energy demand in Sub-Saharan Africa (SSA; excluding South Africa, IEA 2019). The energy efficiency literature hitherto has mostly focused on high-income countries, while energy demand is rising sharply in SSA and Asia (Fowlie and Meeks 2021). More than 3 billion people in the Global South use firewood or charcoal as their main cooking fuel, of which 900 million live in Sub-Saharan Africa. Due to population growth and deficient infrastructure, this number will probably increase in the years to come. Users of firewood emit considerable amounts of carbon in the atmosphere (Bensch et al. 2021) as

[1] Empirical examples for the micro-rebound are manifold, covering energy efficient washing machines in the US (Davies 2008), air conditioning and refrigerators in Mexico (Davies, Fuchs, and Gertler 2014) and energy efficient cars in different high-income countries (Gillingham 2014, Frondel et al. 2008).

firewood is typically used in inefficient open-fire stoves. It is no surprise, therefore, that efforts to promote the diffusion of energy-efficient biomass cookstoves (EEBC) are high on the agenda of policy makers. Depending on the characteristics of the EEBC, the expectation is that improved energy efficiency yields multiple benefits—promoting forest conservation, reducing carbon emissions, and improving the livelihoods of users (including perhaps health benefits due to reduced smoke exposure).

Our study conceptualizes and empirically examines macro-rebound effects due to the diffusion of EEBC. We develop a village-level general equilibrium model, and study how supply and demand of (renewable) biomass interact at the level of village markets. We then use an RCT to study the adoption of EEBC in rural Rwanda. Identification comes from random saturation, where subsidies for adoption of improved stoves are varied at the village level. This design enables exploring how the introduction of EEBC affects individual demand of adopters as well as the local market equilibrium. Empirical research hitherto has focused on micro-level impacts of fuel-efficient cookstoves, and little is known about the magnitude of general equilibrium responses. In our context, the welfare implications of potential rebound effects are ambiguous. If adoption of EEBCs by some households increases access to firewood by (poor) non-adopting households, then this may be undesirable from a carbon-emissions perspective, but possibly preferred from an anti-poverty or livelihoods perspective.

We pre-specified this paper's main hypotheses in a pre-analysis plan (PAP) at the AEA RCT Registry (AEARCTR-0002794). The theoretical model was formalized ex post and makes explicit our thinking on linkages between technology, household behavior, as well as the ecological and institutional factors that determine supply and demand for biomass. It was our ambition to comprehensively depict this complex system of local biomass markets in rural Africa.[2] Specific point estimates reflect possible market outcomes, and outcomes depend heavily on contextual factors – mapping these contextual factors is one of our main goals. In the concluding section, we use the model to carve out shortcomings of our empirical analysis and pinpoint what assessments in new contexts would need to focus on.[3]

[2] It becomes apparent in the empirical part of this paper that the model was not adapted to what we find in the data; indeed, it rather helps to outline the limits of our empirical approach.

[3] We drafted and archived the PAP before household data collection in early 2018. In the few instances where we deviate from the PAP we will indicate this in the text. Apart from the analyses shown in the

Our paper makes theoretical and empirical contributions to the literature. First, our village-level model demonstrates that (general equilibrium) responses to the diffusion of EEBC are complex and varied. In addition to identifying the well-known micro-rebound effect, the model produces a novel mechanism for creating macro-rebound effects. This is based on interaction between the ecological part of the model (biomass growth) and an institutional feature characterizing firewood collection—the common property nature of the resource base. We distinguish between an *incremental* macro-rebound effect and a *transformational* one, where the local ecological-economic system jumps to a qualitatively different equilibrium. Responses to widespread adoption of EEBC depend on local (starting) conditions, and unexpected outcomes (such as where aggregate biomass harvesting increases) are possible. The theoretical model emphasizes the importance of the local context within which energy savings are promoted, in terms of property rights, market integration and biomass.

Our second contribution is based on the RCT with randomly assigned subsidy levels for EEBC across villages in Rwanda. We find that the macro-rebound in this specific context is very small. We study the price elasticity of cookstove demand and find that adoption rates fall sharply as stove prices increase. We use this exogenous variation in village-level uptake to examine effects on the local market for firewood. To gauge macro-rebound effects, we consider effects on firewood collection time and firewood consumption at the individual level, followed by firewood prices and consumption at the local level. Firewood consumption decreases significantly in villages with high saturation levels, driven by firewood savings of adopters. However, there is no clear evidence for impacts on local markets. While firewood prices decline marginally, firewood collection time does not go down, and non-adopters do not change their firewood consumption. The macro-rebound is thus very small.

Based on the theoretical model, we advance three explanations for these findings. First, our empirical approach relies on the assumption of regionally segmented biomass markets.[4] However, these markets could be regionally integrated. If so, firewood production would be shifted from one locality to another, and prices and consumption levels would tend to be

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present paper, we pre-specified to study non-monetary drivers of EBCC adoption as well as general equilibrium effects on norms and beliefs. These outcome variables will be reported in a separate paper.

[4] See Burke et al. (2019) for a similar assumption in a study design to evaluate the impact of post-harvest credit on individual storage and market outcomes.

stable, even accounting for the different levels of saturation we observe. Second, the system could be in a specific 'steady state' where supply is highly price elastic (derived in Section 2). Third, demand for firewood might be relatively inelastic to prices since it is not the binding constraint in food production. If production of crops cannot be increased, households have no use for extra firewood. A fourth possible explanation is low statistical power to pick up village-level effects. In the discussion section we probe these candidate explanations and others, based on details of the production functions of firewood and meals. This further illustrates the importance of context for predicting how the introduction of EEBC affect societal and conservation outcomes.

Together with Carranza and Meeks (2020), who look at macro-rebound effects due to the adoption of energy saving light bulbs in Kazakhstan, this paper initiates a new stream of literature on empirically measuring macro-rebound effects of improvements in energy efficiency.[5] We also contribute to the growing literature on spillover and general equilibrium effects in program evaluation—most of which also applies an identification strategy based on random saturation.[6] Finally, our findings speak to the literature on impacts and adoption of improved cookstoves, which until now concentrates on the individual level (e.g., Alem 2021, Bensch and Peters 2015, Bensch et al. 2015, Berkouwer and Dean 2021, Levine et al. 2018, Mobarak et al. 2012). Various types of improved cookstoves are available, and some impact evaluation studies produced disappointing estimates of welfare effects (e.g., Hanna et al. 2016 and Mortimer et al. 2017). These studies focus on potential health effects by reducing household air pollution but were based on technologies that were ill-adapted to local needs and therefore not used or badly maintained. Instead, the program we evaluate here is based on a robust "down-to-earth" technology that aims to produce immediate and easily-

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[5] Carranza and Meeks (2020) study regional spillovers following the introduction of energy saving light bulbs in Kazakhstan. While they do not frame their results in the context of (macro) rebounds, they can be interpreted as such. Reductions in electricity consumption reduces peak demand and leads to better service quality and reliability of the grid. This, in turn, allows households to increase electricity consumption, reversing some of the initial energy savings.

[6] In Bangladesh, Akram et al. (2018) observe spillover benefits of seasonal migration on labor markets in the village-of-origin. In Mexico, Cunha et al. (2019) find that cash versus in-kind transfers have substantially different impacts on local prices. In India, Muralidharan et al. (2020) and Muralidharan and Sundararaman (2015) study general equilibrium effects of public employment programs and school choices, respectively. Egger et al. (2020) investigate general equilibrium effects of cash transfers in Kenya and Bernard et al. (2019) study adoption spillovers for an improved seeds intervention in DRC.

observable fuel savings rather than opaque health benefits. Such technologies have been found to be well adopted, used intensely and to deliver important resource savings (Berkouwer and Dean 2021, Bensch and Peters 2020, Bensch et al. 2015, Gebreegziabher et al. 2018, Pattanayak et al. 2019).

The paper is organized as follows. In section 2 we provide a simple general equilibrium model that brings together supply of, and demand for, food, energy and "other goods" at the village level. The basic model focuses on the collection of branches, lopped from standing vegetation. In an appendix we also consider the complementary case of collecting twigs from the forest floor. In section 3 we introduce the context and the RCT and present our data and identification strategy. Section 4 contains the empirical results, focusing on individual-level effects (micro-rebound effects) and village-level effects (macro-rebound effects). In section 5 we interpret the empirical findings in light of the theory and propose a context-specific amendment to the general model to explain the main results. The conclusions ensue.

2. Theory

We present a stylized theoretical model to guide our thinking about how an energy efficient technology triggers equilibrium responses if fuel is produced and consumed locally.[7] We develop a village-level general equilibrium model where commodity and factor prices adjust in response to the introduction and uptake of EEBC. The model predicts how prices and consumption shares of key commodities adjust (food, energy, other goods); the re-allocation of labor across productive activities; and the effect of EEBC on the forest stock.

We focus on a simple village economy with a unit mass of households. Markets clear locally, and prices are determined by equating supply and demand. To solve the model, we develop three building blocks: (i) local demand for commodities, (ii) local supply of these same commodities, and (iii) the evolution of the biomass stock that serves as a source of renewable energy. We discuss these building blocks in turn.

[7] As outlined in the introduction, we formalized the theory ex-post. The model is more comprehensive than what we can observe in our empirical data, and provides a general framework to discuss the context dependency of our empirical results.

2.1. Demand side

Households derive utility from consuming food (*f*) and a broad category of other goods & services (x). The latter category lumps together simple *manufactures*, but also all types of services that are locally produced and consumed (e.g. transport, construction work, repair and maintenance, informal care). The Cobb-Douglas utility function of the representative household reads as follows:

$$U = x^{\alpha} f^{1-\alpha}. \tag{1}$$

To produce food, households combine crops (c) and biomass (b). The latter is a source of energy. Emphasizing that energy and crops are complements in food production, we assume food production may be described by a Leontief production function;[8]

$$f = min(c, \theta b), \tag{2}$$

where θ is a parameter measuring the efficiency with which biomass is converted into usable energy. EEBC are stoves with higher values of θ. We refer to b as biomass extracted, and θb as "effective energy". For an optimal outcome, households consume crops and energy in fixed proportions; $c = \theta b$.[9]

Households maximize utility subject to a budget constraint;

$$1 = x + p_c c + p_b b = x + p_c \theta b + p_b b. \tag{3}$$

In (3), we normalize full household income and the price of *other goods & services*, setting them equal to 1. Income captures both monetary and in-kind income (subsistence production). Next, p_c is the price of crops and p_b is the price of biomass. Prices may, but need not be, expressed in monetary terms—they simply express the rate at which commodities can be locally exchanged.[10] From the first order conditions, a share α of income will be spent on manufactures and a share $(1-\alpha)$ will be spent on food (i.e. crops and energy). Hence:

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[8] This is a simplification because we ignore potential economies of scale in cooking. Cooking twice as much stew does not always require twice as much biomass.

[9] In a deterministic model, crops and biomass are supplied in this optimal proportion. In stochastic models, with uncertain supply, either biomass or crops can be a limiting factor in the preparation of food. Our qualitative evidence suggests that, in practice, the availability of crops is often a limiting factor (presumably reflecting that supply of biomass is more flexible and responsive to temporary scarcity).

[10] For example, firewood in rural Africa is often collected by households themselves and not necessarily bought at markets. Subsistence production is an important source of the crops that are consumed.

$$1 - \alpha = p_c \theta b + p_b b. \tag{4}$$

We can rewrite (4) to obtain;

$$p_c = \frac{(1-\alpha) - p_b b}{\theta b}, \text{ or} \tag{5a}$$

$$p_b = \frac{(1-\alpha) - p_c \theta b}{b}. \tag{5b}$$

These expressions capture that expenditures on crops will decline as the price of biomass increases, and vice versa. This follows directly from the fixed proportions assumption.

The consumption-side of improved stove adopters is readily linked to the *micro rebound*. The literature distinguishes between direct and indirect micro rebound effects. Gillingham et al. (2016, p.72), write that "the effect of an energy efficiency increase on the demand for all other goods and the subsequent change in energy use is called the indirect rebound effect". Because of offsetting income and substitution effects, a consequence of Cobb-Douglas utility, our model does not feature such indirect rebound effects. Before and after adopting, adopters spend fraction α on consuming other goods and services, so there is no change in (indirect) energy usage.[11] The direct rebound effect, however, materializes in our model. An increase in energy efficiency will, first, reduce demand for biomass. The income unspent is subsequently allocated to crops and biomass (in the fixed proportion $c = \theta b$), so total food production increases. This second-round increase in biomass production is the traditional direct micro rebound.

2.2. *Supply Side*

Next, turn to the village´s supply side. Households allocate labor to the production of crops, "other goods & services", and biomass. To avoid notational clutter, but without much loss for the qualitative insights obtained later, we consider the simplified case of production functions that are linear in labor over the relevant range. For example, we assume:

$$c = \beta l_c, \text{ and} \tag{6}$$

$$x = l_x. \tag{7}$$

[11] This would change for alternative specifications of utility. If the income effect dominates the substitution effect (for a CES utility function, say), then an increase in energy efficiency would produce an indirect rebound effect.

In (6), β is a scaling parameter and l_c and l_x represent labor allocated to the production of crops and "other goods & services", respectively.

Next, we turn to the production of biomass. Motivated by our rural Rwandan context, we distinguish between two types of biomass collection: households can collect twigs from the forest floor or cut branches from standing trees. Denote X as the stock of twigs, and R as the standing forest (biomass) stock. We treat twigs and branches as sources of biomass, and assume these sources of energy are perfect substitutes.[12] Reflecting that it is easier to extract biomass when it is abundant, we assume harvesting of biomass is described by Schaefer production functions;[13]

$$b = Max[qRl_b, vXl_b] \tag{8}$$

where q and v are scaling coefficients that capture the efficiency of the harvesting mode (usually referred to as catchability coefficients in fishing applications), and l_b is labor allocated to harvesting biomass. Since the twig and branch production functions are both linear in labor, households will specialize in one activity (a corner solution).[14] In the main text we consider the case where households cut branches as the source of biomass. In an Appendix we also discuss twig collection, and the case where both biomass sources are utilized. These additional cases further emphasize a key insight of the theoretical model, namely that responses of the ecological-economic system are complex and context-specific.

The labor budget constraint for the village is:

$$1 - x = l_b + l_c.$$

We assume there is free entry in the tree production sectors, or that villagers can freely choose where to allocate their labor. This implicitly assumes that individual property rights to the forest resource do not exist or are not enforced. Instead, the forest stock is a common property resource. Free entry implies that the returns to labor across the three sectors must be

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[12] This implies we ignore potential issues related to fuel switching (e.g., Chan and Gillingham 2015).

[13] The Schaefer production function is the workhorse specification of the harvest function in renewable resource economics (Clark 1990), and a building block of the famous Gordon-Schaefer fishing model.

[14] They will switch back-and-forth between collecting twigs and cutting branches, depending on where labor generates the greatest amount of energy. Hence, (8) is a no-arbitrage condition. For $vX > qR$, households collect twigs, and for $vX < qR$, households cut branches.

equalized (no-arbitrage condition). Equalizing the average return to time spent producing crops to the return to producing "other goods & services" yields the following:

$$p_c\beta = 1 \rightarrow p_c = \frac{1}{\beta}. \tag{9a}$$

Similarly, villagers should be indifferent between biomass collection and producing "other goods and services":

$$p_b qR = 1 \rightarrow p_b = \frac{1}{qR}. \tag{9b}$$

In the village-level equilibrium, demand side prices should equal supply side prices. We are agnostic about which villagers undertake which activities. Hence, the village economy may be characterized by (mainly) specialized production and subsequent trading between households, or (mainly) by subsistence production. This is immaterial. Equating the right-hand side of (5a) and (9a), and simplifying, gives us the aggregate amount of biomass collected and consumed in equilibrium:

$$b = \frac{\beta(1-\alpha)qR}{\beta+qR\theta} \tag{10}$$

Condition (10) produces an intuitive but important result; keeping the forest stock R constant, an increase in the performance of cookstoves will reduce the amount of biomass collected, i.e.:

$$\frac{\partial b}{\partial \theta}|_R < 0. \tag{11}$$

2.3. *Forest Growth*

To "close the model" and characterize its long-term steady states, we analyze how the forest stock, R, evolves over time. Biomass extraction by cutting branches draws down the standing forest, but the forest is a renewable resource with the potential to regenerate and replenish itself. Assuming that resource growth is described by a conventional logistic growth function, we obtain the following equation of motion for the forest stock;

$$\frac{dR}{dt} = G(R) - b = rR\left(1 - \frac{R}{K}\right) - qRl_b \tag{12}$$

Where $G(R)$ is the growth function, r is the intrinsic growth rate and K is the carrying capacity (r and K are both parameters). In the steady state $\left(\frac{dR}{dt} = 0\right)$, biomass extraction equals biomass growth: $G(R) = b$. This yields a quadratic equation for the steady state;

$$\left(\frac{rq\theta}{K}\right)R^2 + \left(\frac{r\beta}{K} - rq\theta\right)R + \beta q(1-\alpha) = 0. \tag{13}$$

Depending on parameters, (13) can be solved and yields zero, one or two positive values of R as the outcome (where $0 \leq R \leq K$). Only stable outcomes are relevant as equilibria, and these are outcomes where the biomass extraction curve $b(R)$ intersects the growth function $G(R)$ from below. An example of such a stable equilibrium, called R_1, is provided in Figure 1. It defines the steady state forest stock and biomass extraction level.[15]

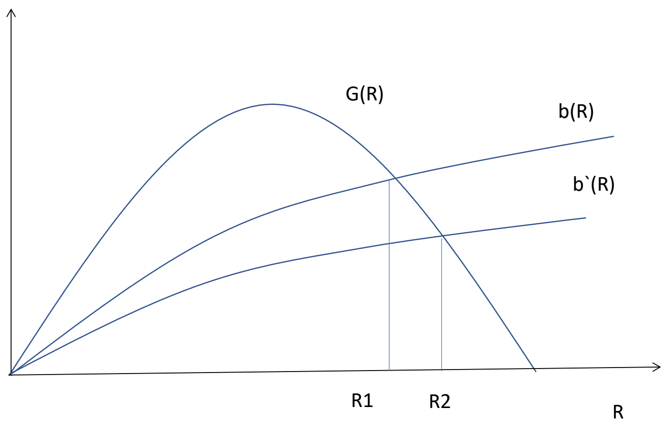

Figure 1: Theory - Steady state forest growth and biomass extraction

With these three building blocks in place, we can evaluate the consequences of introducing EEBC (with $\theta' > \theta$). From (11) we know that this will shift down the extraction curve $b'(R)$. As a result, a new steady state forest stock, R_2, emerges. This process is also depicted in Figure 1. For the case drawn in Figure 1, introducing EEBC will increase the steady state forest stock and reduce steady state biomass harvesting. But this is not the only possible outcome.

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[15] For different combinations of parameters, there may also be two steady states or no internal steady state. Two steady states emerge if the $b(R)$ curve is sufficiently steep as to be *initially located above* the $G(R)$ curve, for low forest stock sizes and then cuts the growth function $G(R)$ from above. The first steady state, where the $b(R)$ intersects the $G(R)$ curve from above, is unstable. Denote this steady state by R^*. For initial stock sizes below this unstable steady state ($R(t_0)<R^*$), the forest stock will be harvested down until it is fully depleted (R=0). For initial stock sizes above the unstable steady state ($R(t_0)>R^*$), the forest stock will grow until it reaches the other steady state, R_1, which is stable. There are no internal steady states if the $b(R)$ curve is *always* located above the growth function. In that case, the forest will be overharvested until it is depleted (R=0).

2.4. *Economic and ecological equilibrium*

To explore how the economic-ecological system responds to an increase in energy efficiency, we analyze demand and steady state supply in more detail. The demand curve for biomass follows from combining (5a) and (9a):

$$p_b = \frac{1-\alpha}{b} - \frac{\theta}{\beta}. \tag{14}$$

This is a downward sloping demand curve. Quantity demanded (b) approaches zero as p_b approaches infinity, and the demand curve intersects the quantity axis at $b = \frac{\beta(1-\alpha)}{\theta}$. From (14), increasing stove efficiency shifts demand down. This is an intuitive result.

The supply curve is more complex. From (9b), $R = \frac{1}{qp_b}$. Inserting this expression in growth function, $G(R)$ gives us the sustained yield in terms of the biomass price:

$$b = \frac{r}{p_b q}\left(1 - \frac{1}{p_b qK}\right). \tag{15}$$

This is the equilibrium supply curve for open access biomass extraction. Output is zero for $p_b < 1/qK$ and is maximized at $p_b=2/qK$. This is the maximum sustainable yield. If prices increase further, steady state supply decreases and eventually approaches zero as p_b goes to infinity. Increased resource scarcity (and higher prices) will crowd in additional extraction effort. Beyond the maximum sustainable yield level, however, this will depress steady state harvesting—a case of overexploitation. This happens when the extraction curve $b(R)$ in Figure 1 shifts up, and starts intersecting the growth function to the left of the top of the parabola. The resulting backward bending supply curve is drawn in Figure 2.

We have also drawn two different demand curves; D_1 and D_2. D_1 indicates the case where demand for biomass is relatively "low".[16] Demand equals supply in point A, which defines the equilibrium quantity b^* and price p_b^*. A small increase in stove efficiency shifts A further to the left. The equilibrium supply curve is highly elastic around A because overall firewood extraction is low and can be easily increased at low marginal costs. Hence, the result

[16] This may happen, for example, if villagers spend a small share of their income on food (low α) or use unproductive agricultural technologies (low β).

will be a relatively large decrease in the quantity harvested and a small effect on the equilibrium price.

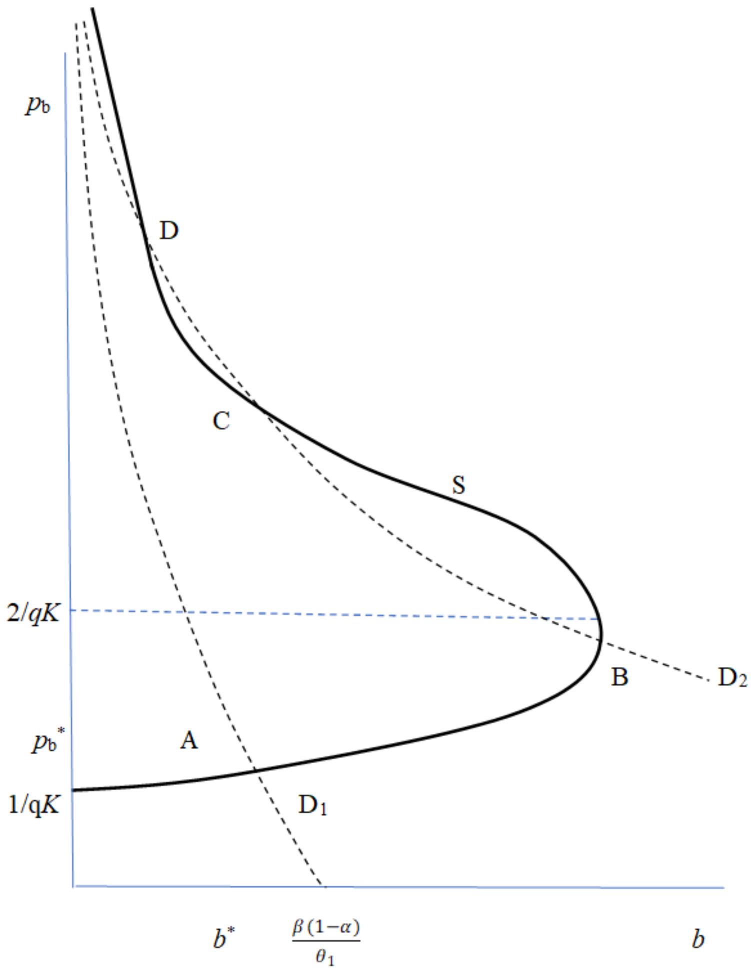

Figure 2: The long-term general equilibrium of the bioeconomic model.

Notes: D1 and D2 refer to two demand curves and S refers to the backward-bending supply curve. Demand curve D2 gives rise to three possible steady states, two of which are stable (B and D) and of which is unstable, C.

In a context with greater demand for biomass, *ceteris paribus*, demand curve D_2 provides the relevant description. Two observations are relevant: (i) there are now multiple steady states, two of which are stable (B and D)[17], and (ii) the comparative statics of these steady states are potentially different. Depending on initial values (i.e. whether the system "starts" to the left or the right of separation point C), it will settle at equilibrium B (low prices,

[17] Steady state D is not provided in Figure 1. This steady state would emerge if the harvest curve $b(R)$ were initially steeper and also cut the growth function below to the left of the top of the growth function.

abundant supply of biomass) or equilibrium D (high prices, low levels of biomass supply). Since the supply curve has negative slope in equilibrium D and a positive one in B, it follows that the comparative statics with respect to improving energy efficiency are different. Specifically, "shifting down" demand curve D_2 implies that new equilibria will materialize along the supply curve. Starting in steady state B, prices and biomass quantity will both decrease. The supply curve is inelastic ("steep") in B, so there will be a large fall in prices and a relatively small decrease in quantity harvested and consumed. In contrast, starting in steady state D, prices will fall but the quantity of biomass supplied and consumed increases.

Observe that discontinuous responses are also possible if multiple stable steady states exist (as with demand curve D_2). Assume that the system is initially in D. Introducing an improved stove shifts down the demand curve D_2. Stable equilibrium D shifts down and unstable equilibrium C shifts up. Further shifting down the demand curve, for example due to successful diffusion of EEBCs in the community, will cause these two steady states to gradually approach each other, then they merge, and then they disappear. A bifurcation occurs, and the system "jumps" to the new steady state B—with much lower prices and much larger biomass quantities harvested.[18]

This identifies a new type of macro-rebound effect. If the system is initially in steady state D, then increasing energy efficiency will *increase* the steady state quantity of biomass that is harvested and consumed. Note that from a nature conservation perspective, this increase is positive, because the standing forest in the new equilibrium is bigger than before, and more biomass can be harvested sustainably. The macro-rebound effect is a consequence of backward bending supply, which is the result of the interaction between the system's ecological underpinnings (logistic growth) and the absence of property rights to the forest resource. Two types of macro-rebounds can occur. For small shifts in the extraction curve, the steady state adjusts incrementally along the supply curve. This may be referred to as an incremental macro-rebound. For larger shifts in the extraction curve, the bifurcation occurs and the system settles

[18] Conversely, if the demand curve shifts out (due to a change in preference parameter α, production parameter β, or a decrease in technical efficiency), then steady states B and C approach each other, and may eventually merge and even disappear. In that case an economic-ecological system starting in B collapses to steady state D, with much higher prices and smaller biomass quantities harvested (and a degraded forest stock).

at the new equilibrium B. This may be referred to as a shock, or a transformational macro-rebound. These macro-rebounds complement the micro-rebound effect discussed above.

2.5 Model predictions

The village-level general equilibrium model therefore generates the following sets of testable predictions for the long-term, after when *R* moved to a new steady state:

Proposition 1. *In the long term, after the forest stock R has reached a new steady state, the introduction of an EEBC (with $\theta' > \theta$) will have the following effects.*

A. *EEBC will not affect the production, consumption or prices of other goods and services;*
B. *EEBC will induce villagers to re-allocate some of their labor from biomass collection to crop production ($l_b \downarrow, l_c \uparrow$), which will …*
C. *… increase the steady state forest stock ($R \uparrow$) and …*
D. *… increase production and consumption of crops ($c \uparrow$), effective energy ($\theta b \uparrow$), and food ($f \uparrow$);*
E. *EEBC have an ambiguous effect on biomass harvested ($b \downarrow\uparrow$);*
F. *EEBC will reduce the relative price of biomass.*

Result A follows from the assumption of Cobb-Douglas utility, which implies that income and substitution effects of *EEBC* cancel. Villagers always use share α of their time (budget) to production (consumption) of "other goods & services". Result B follows from the finding that, per unit of crop, less biomass is needed to produce a unit of food. As a result, some labor is re-allocated from biomass harvesting to crop production (equations 10 and 11). Result C follows from Result B and Figure 1. Result D follows directly from Results B and C. Result E follows from Result C combined with the non-linearity in the forest growth function. Depending on whether extraction function *b*(*R*) intersects the growth function *G*(*R*) to the left or the right of the top of the growth function, steady state biomass harvesting increases or decreases as the steady state stock *R* grows. Result F follows from Result C combined with no-arbitrage condition (9b).

3. Background on program under evaluation and research approach

3.1. *Cooking in rural Rwanda*

Firewood and charcoal are the main cooking fuels for more than 3 billion people and the dominant primary energy source in much of Sub-Saharan Africa and South Asia. Collection of firewood is often time-intensive: In rural Rwanda, 82 percent of households collect firewood and spend on average more than 300 minutes per week on this task (our data)—especially women and children (Martin et al. 2011). Cooking with wood fuels causes adverse health outcomes due to unclean combustion processes (WHO 2016). From an ecological and climate perspective, woodfuels are an important determinant of deforestation (e.g. Bailis et al. 2015). Deforestation is responsible for 6-17 percent of global anthropogenic carbon dioxide emission (Bacchini et al., 2012), and woodfuel-induced emissions in Sub-Saharan Africa are comparable to the total emissions of a large, industrialized country like Germany. While the international community focusses on promoting clean fuels or stoves to combat local and global air pollution, the Government of Rwanda (GoR) perceives the firewood reduction effect as more pressing. This reflects the growing scarcity of biomass in the country.

In recent years, the GoR's has focused on promoting access to electricity. The huge Electricity Access Roll-Out Plan absorbs much of the administration's capacity and budget (see Lenz et al. 2017). Except for the privately funded DelAgua improved stove program (Rosa et al. 2014) there have only been sporadic and regionally limited improved stove interventions. In 2010, the GoR, through its implementing agency EWSA, launched the first phase of a national promotion program for a simple EEBC called *Canarumwe* in rural areas of 15 of Rwanda's 30 districts.[19] A second phase targeted the remaining 15 districts in 2014. Promotion was limited to setting up stove production units and training of producers. The approach is based on a market-based paradigm, and people are expected to pay cost-covering prices.

What exactly constitutes an "improved" or "clean" stove remains debated (e.g., Jetter et al. 2012). The Canarumwe stove is at the lower end of the spectrum. It is a low-cost clay stove designed to reduce firewood consumption, but not to reduce air pollution. Since it cannot be expected to yield positive health effects, we refer to the Canarumwe as an energy-

[19] The first phase also promoted a charcoal stove in urban areas called *Canamake*.

efficient biomass cookstove (EEBC).[20] The Canarumwe stove is locally produced and the costs including in-house installation amount to 2,500 FRW (~3 EUR).[21] These seemingly low investment costs still correspond to around 4 percent of households' monthly expenditures, which amount to around 65,000 FRW in rural Rwanda (Lenz et. al 2017).

The Canarumwe runs on firewood, the most common cooking fuel in rural Rwanda. Firewood in the country is mainly collected. According to our data, 80 percent of the households collect their own biomass and around 20 percent of households buys firewood on the local market. Hardly any households use charcoal, LPG, or kerosene for cooking. Branches and twigs of firewood are sometimes mixed with agricultural residues or leaves if firewood is not sufficiently available, or if agricultural residues are abundant after harvesting. Due to high transport costs, the market for firewood is highly fragmented. Firewood is rarely transported across villages. People collect their own firewood near their plots, close to their houses. Traded firewood is normally also sourced in the immediate vicinity of the village.

3.2. *Program under evaluation and research approach*

To test alternative policy scenarios, EWSA piloted target group-oriented sensitization during the second phase of the national cookstove program starting in 2014. In addition, to test the affordability constraints of intended beneficiaries, EWSA explored different subsidy regimes. We partnered with EWSA to design this pilot as a cluster RCT.[22] In October 2014 we selected 84 villages from the program population and randomly allocated them to a control group or one of three treatment arms: a high subsidy, a medium subsidy and a no subsidy arm (21 villages per experimental arm). Villages were drawn from six out of 15 districts in which EWSA supported the installation of stove production units. We compiled a comprehensive list

[20] Just as the Canarumwe, similar EEBC like the Jiko stove that have been widely distributed or disseminated across Africa, from a public health perspective cannot be expected to reduce air pollution to a sufficient degree (see Jetter et al. 2012).
[21] The Canarumwe is produced in two steps. First, the clay inlay is produced at stove production units, mostly located in peri-urban areas. Next, this clay inlay is transported to the village where it is installed inside a household's kitchen using locally made bricks. For this task, EWSA trains installers, typically local craftsmen who live in rural areas. EWSA did not foresee centrally planned awareness raising campaign in villages—marketing activities were left to the installers.
[22] The cooperation was initiated by one of our co-authors, Anicet Munyehirwe, who had been contracted by EWSA under the national cookstove program to set-up the stove production units in our six study districts.

of non-adjacent cells (in order to avoid treatment contamination) and took a random draw of cells (see Annex 3 for maps used to identify these cells). One cell comprised several settlement clusters, and we randomly selected one *umudugudu* within the cell for treatment. The *umudugudu* is the lowest administrative entity in Rwanda and is often smaller than a settlement cluster that one would commonly define as a village. One settlement cluster normally consists of two to three *umudugudus*. Even though not completely accurate, we refer to the *umudugudu* as a village in what follows.

In the three treatment arms, stove production units and installers were trained in a business-as-usual way, i.e. just as in other parts of the country. Furthermore, we also arranged a marketing event in each of the treatment villages in cooperation with installers, informing households about Canarumwe's main advantages and usage instructions. These events took place between May and August 2015. Rural dwellers in the villages could order the EEBC right after this marketing event, but also on a rolling basis. The three arms only differed in the price at which the stove inlay and installation was offered: FRW 0, FRW 1,250 and FRW 2,500. Additional to these costs, households had to contribute bricks, sand, and water for installing the stove inlay in the household's kitchen. These inputs are locally sourced at no monetary cost. Ordered EEBCs were installed in the weeks following the event. Households in the no-subsidy and medium-subsidy arms could make payments in installments, to mitigate concerns about liquidity constraints. No marketing activities took place in control villages.

In many villages, village chiefs requested follow-up marketing events as people in the villages started to learn about the EEBC from early adopters. Our field team conducted up to two additional visits to these villages. These additional visits were more frequent in villages where stoves were distributed at a high subsidy.[23] Again, households could make orders after this second marketing event, and on a rolling basis.

This set-up enables us to study the price elasticity of EEBC demand. Adoption rates fall sharply as prices increase, which causes exogenous variation in the saturation level of EEBC

[23] The additional visits were a result of substantial interest in the villages and were requested by the villages. Our field team did not propose pro-actively to visit high subsidy villages more frequently. Accordingly, the frequency of the visits is a consequence of the level of subsidy and thereby an intermediate outcome rather than a confounder.

across arms. We use this variation to study how energy-efficient stoves affect the market price of firewood, firewood collection time, and firewood consumption.

For estimating adoption rates, we estimate the following equation:

$$Y_{ic} = \alpha + \beta_{\text{high}} T_c^{high} + \beta_{\text{medium}} T_c^{medium} + \beta_{\text{control}} T_c^{control} + \varepsilon_{iC} \quad \text{(16a)}$$

where Y_{iC} is an indicator variable reflecting the take-up decision for household i in community c. The binary variables T_c indicate whether community c was randomly assigned into the high subsidy, medium subsidy, or control group. β measures the intention to treat and captures the difference in adoption, compared to adoption in the no subsidy group. We cluster standard errors at the community level.

As a robustness check, we control for community-level and household-level characteristics that might affect outcomes but are arguably unaffected by the treatment. On the community-level, we use characteristics of EEBC installers (involvement in earlier campaigns), distance to main road, access to public transport, mobile phone signal availability, existence of public infrastructure, and electricity grid access. On the household-level, we use household size, education of the head of household, age of the head of household, house construction materials, and ownership of animals and means of transportation.

For impacts at the village level, we slightly adjust equation 16a, and define random assignment to the control group as the base case:

$$Y_{ic} = \alpha + \beta_{\text{high}} T_c^{high} + \beta_{medium} T_c^{medium} + \beta_{no} T_c^{no} + \varepsilon_{iC} \quad \text{(16b)}$$

where Y_{iC} is the outcome of interest for household i in community c and β accordingly captures the difference in outcomes, compared to the outcome level in the control group. The binary variables T_c indicate whether community c was randomly assigned into the high subsidy, medium subsidy, or no subsidy group. Again, we cluster standard errors at the community level and control for community- and household-level characteristics as a robustness check. [24]

[24] In contrast to what was specified in the PAP, we do not control for village dummies when estimating individual level outcomes. Controlling for village dummies is not appropriate in this setting because treatment assignment is also at the village level, which leads to multi-collinearity issues.

In a second step, we look at effects at the household level, where we distinguish between adopters and non-adopters. Since adoption is not random, we use propensity score matching (PSM) to create a counterfactual from control villages. This matching exercise is done for each subsidy level separately. We explain variation in adoption status for each treatment arm by several covariates, and use coefficients from this probit model to predict the probability of adopting for each household in the respective treatment arm subsample and control arm.[25,26] These predicted propensity scores are used to match adopters to households from the control areas using the Kernel matching algorithm (matching each adopter to a weighted average of all control households, with weights depending on similarity in propensity scores).[27]

For analyzing impacts among adopters and non-adopters, we estimate the following equations for each subsidy level and adoption status separately.

$$Y_{adopt\_high\_i\_C} = \alpha + \beta_{\text{high\_adopt}} T_c^{high} + \varepsilon_{iC} \tag{17}$$

$$Y_{adopt\_medium\_i\_C} = \alpha + \beta_{\text{medium\_adopt}} T_c^{medium} + \varepsilon_{iC} \tag{18}$$

$$Y_{adopt\_no\_i\_C} = \alpha + \beta_{\text{no\_adopt}} T_c^{no} + \varepsilon_{iC} \tag{19}$$

$$Y_{nonadopt\_medium\_i\_C} = \alpha + \beta_{\text{medium\_nonadopt}} T_c^{medium} + \varepsilon_{iC} \tag{20}$$

$$Y_{nonadopt\_high\_i\_C} = \alpha + \beta_{\text{high\_nonadopt}} T_c^{high} + \varepsilon_{iC} \tag{21}$$

$$Y_{nonadopt\_no\_i\_C} = \alpha + \beta_{\text{no\_nonadopt}} T_c^{no} + \varepsilon_{iC} \tag{22}$$

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[25] This approach of calculating the propensity scores was originally applied in Bensch et al. (2011), Peters et al. (2011) and Lenz et al. (2017). Details of the probit estimation results and balancing of covariates can be found in the Appendix.

[26] In the PAP, we did not pre-specify that we would use PSM to identify counterfactual adopters and non-adopters in the control group. However, we deem the PSM approach superior to account for non-random selection into adoption than simply interacting adoption and treatment status as specified in the PAP. This change does not matter for the main interpretation of the results or the conclusions.

[27] We did not randomize EEBC assignment within the villages in order to study price-elasticity of EEBC uptake under real-world policy conditions. This precludes us from using standard models to study interference in two-stage randomized saturation designs as proposed for example by Baird et al (2018).

where $\beta_{\text{high\_adopt}}$ ($\beta_{\text{medium\_adopt}}$; $\beta_{\text{no\_adopt}}$) measures the average treatment effect of the treated in the high subsidy group (medium; no subsidy) and captures the difference in outcomes, compared to the outcome level among matched control households identified and weighted according to the PSM approach. For each estimation, the sample is restricted to adopters in the respective treatment group and matched observations from the control group.

$\beta_{\text{high\_nonadopt}}$ ($\beta_{\text{medium\_nonadopt}}$; $\beta_{\text{no\_nonadopt}}$) measures the average treatment effect of the non-treated in the high subsidy group (medium; no subsidy) and captures the difference in outcomes, compared to the outcome among matched control households identified and weighted according to the PSM approach. Again, the sample is restricted to non-adopters in the respective treatment group and matched observations from the control group. Standard errors are clustered at the community level, and we control for community- and household-level characteristics as a robustness check.

3.3. Data collection and impact indicators

We rely on three data sources: household and village surveys implemented in February and March 2018, and data from follow-up qualitative research in March 2020. The household survey covers around 20 randomly chosen households in each of the 84 villages (N=1672). We elicited data regarding (i) household members' demographic information, occupation, education status, and daily time use; (ii) current household energy use (energy sources, time spent collecting fuel, expenditure, technologies used, locations used, kitchen ventilation, which household members are responsible for energy purchase and use); and (iii) household consumption, income and expenditure.[28] The village survey ran in parallel with the household survey, and was used to gather information from the village chief. The qualitative survey involved field visits to 2-3 villages per study district (*N*=14 villages in total). Within each village, semi-structured interviews with households and wood-sellers were conducted. The interviews focused on questions regarding firewood collection and usage patterns, as well as observations on the local firewood market. The analyses are further informed by some of the

[28] For households that received an EEBC, we include a survey section on understanding of the EEBC, sources of information that influenced the adoption decision, and opinions about the technology.

authors' longstanding practical field knowledge on living conditions and local economies in rural Rwanda, particularly on the cooking and biomass sector.

Adoption of EEBC is measured in two ways: First, we elicit the share of households that ordered a stove. The share is calculated relying on the household survey, in which we ask households directly whether they ordered the EEBC. Second, we elicit the share of households that effectively uses the stove. Here, we rely again on the household survey, which elicits stove usage by direct questions. For measuring the *market price for firewood*, we ask the village chiefs for the maximum price and minimum price paid over the year. We also ask all households that buy firewood how much they paid for firewood. For measuring *collection time for firewood*, we ask households about who collects firewood in the household, how often they collect firewood per month, and how long it normally takes them. For *household firewood consumption*, we rely on subjective questions and weighed measures of fuel use. We ask each household which meals they prepared on the last cooking day and asked them to estimate the amount of fuel used for this meal for each stove used. The indicated amount of fuel was subsequently weighted with a hand scale by our enumerator.

3.4. Randomization balance

Since we do not have baseline data, for our balancing test we rely on household and village variables measured in 2018 that we believe are unaffected by the treatment. Both on the households and the village level, groups are not perfectly balanced in all dimensions (see Table 1). We see some statistically significant differences, of which some are also important in size. Particularly, some village characteristics are notably different. For example, road access conditions are substantially worse in the high subsidy villages. At the same time, these villages seem to be slightly better off with regards to mobile phone connectivity or access to grid electricity. Overall, no clear distortion into one direction emerges. We will include covariates in some of the models that we estimate to control for pre-existing differences, and to increase the precision of our estimates.

Table 1: Randomization balance at household and village level

Variable	mean cntrl (1)	no subsidy (2)	med subsidy (3)	high subsidy (4)	t-test, p-value (1)-(2)	(1)-(3)	(1)-(4)	(2)-(3)	(2)-(4)	(3)-(4)
Households Characteristics										
household has separate kitchen	0.79	0.79	0.83	0.81	0.924	0.453	0.662	0.321	0.531	0.707
Hoh visited at least alphabetization courses	0.58	0.62	0.55	0.56	0.306	0.588	0.718	0.128	0.145	0.821
=1 Head of household is female?	0.26	0.29	0.27	0.25	0.470	0.876	0.656	0.561	0.280	0.556
Age of head of household	48.35	47.73	48.81	49.43	0.639	0.686	0.408	0.314	0.174	0.556
number of household members including children	4.97	4.91	4.80	5.14	0.722	0.287	0.283	0.522	0.181	0.038**
wall material is better than wood or clay/mud	0.43	0.45	0.43	0.42	0.825	0.995	0.951	0.828	0.772	0.958
soil material is better than earth	0.11	0.11	0.16	0.16	0.977	0.341	0.223	0.329	0.187	0.903
household owns cows	0.46	0.43	0.34	0.45	0.745	0.127	0.922	0.183	0.832	0.166
household owns goats and/or sheep	0.35	0.37	0.37	0.44	0.619	0.564	0.063*	0.956	0.170	0.175
household owns pigs	0.15	0.16	0.16	0.20	0.942	0.904	0.401	0.963	0.436	0.448
USD-monthly overall non-energy HH expenditures	46.68	47.45	48.45	44.39	0.858	0.784	0.589	0.872	0.423	0.510
household saves money formally or informally	0.58	0.63	0.67	0.59	0.310	0.078*	0.937	0.351	0.347	0.089*
N	*422*	*418*	*418*	*413*						
Village Characteristics										
distance to the main road in km	16.79	20.76	19.43	20.86	0.502	0.582	0.410	0.824	0.988	0.777
access road to village is dirt road[1]	0.48	0.48	0.52	0.86	1.000	0.765	0.008***	0.765	0.008***	0.019**
installer participated in earlier stove campaigns	n/a	0.10	0.19	0.14				0.390	0.644	0.688
access to public transport easy or very easy	0.29	0.38	0.48	0.38	0.524	0.213	0.524	0.544	1.000	0.544
mobile phone network is good	0.57	0.52	0.52	0.71	0.764	0.764	0.346	1.000	0.213	0.213
cell bureau in village	0.24	0.05	0.19	0.10	0.081*	0.715	0.224	0.160	0.560	0.390
any type of school in village	0.14	0.10	0.24	0.14	0.644	0.444	1.000	0.224	0.644	0.444
any type of health infrastructure in village	0.10	0.00	0.00	0.05	0.154	0.154	0.560	N/A	0.323	0.323
access to national electricity grid in village	0.43	0.29	0.33	0.43	0.346	0.537	1.000	0.746	0.346	0.537
number of inhabitants in village	1319	668	739	754	0.233	0.297	0.305	0.564	0.382	0.924
number of households in village	178	148	178	163	0.331	0.994	0.669	0.149	0.484	0.581
N	*21*	*21*	*21*	*21*						

Notes: The value displayed for t-tests are p-values. Standard errors are clustered at the village level. ***, **, and * indicate significance at the 1, 5, and 10 percent critical level. [1] dirt road is opposed to a gravel road or in very rare cases a paved road.

4. Results

4.1. Adoption of EEBC

Figure 3 shows that EEBC adoption is price elastic and adoption rates increase substantially at lower prices. These patterns are robust to various ways of defining 'adoption'. We distinguish whether households obtained the stove in the first place, whether this stove is still usable, whether it is regularly used, and whether it has been used on the last cooking day. Most households that ordered a stove still have this stove and it is in usable conditions. A somewhat lower share uses the stove regularly, and used it on the last cooking day. The difference between ownership and usage is most pronounced in the high subsidy arm. Even if we only consider usage of the EEBC as actual adoption, the adoption rate stands at almost 40 percent in the high subsidy arm. In the following, we define adoption as having used the EEBC on the last cooking day.[29] [30]

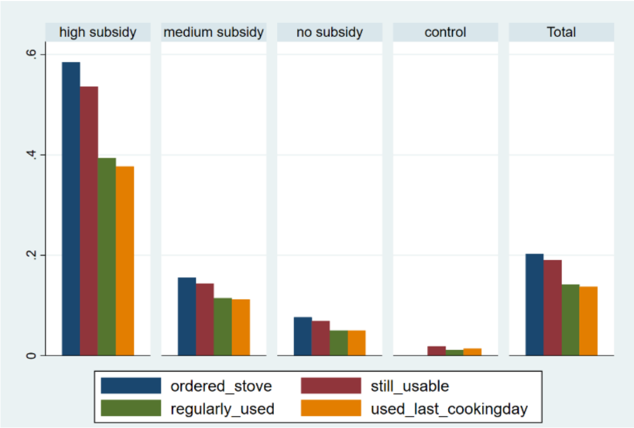

Figure 3: Adoption of Canarumwe, external and internal margin.

Notes: ordered stove: direct question whether HH ordered stove after our marketing activities in 2014/2015; still usable: open question on which usable stoves exist in the HH; regularly_used: open question on which meals are prepared in a typical week and on which stove; used_last_cookingday: open question on which meals were prepared on the last cooking day and on which stove.

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[29] The data in Figure 3 speak to the question whether key inputs should be distributed at zero cost to poor households, or that they should be sold, possibly at subsidized prices (e.g. Cohen and Dupas 2010). One argument in favor of cost sharing is that positive prices have a screening function—promoting that inputs are actually allocated to those households who value them. While earlier studies found very high usage rates for free cookstoves (Bensch and Peters 2020), it is evident that the share of households who received and actually used the stove is higher for households in the no subsidy arm than in the high subsidy arm.

[30] Regressing the adoption indicators on the treatment arms (base=no subsidy arm) show statistically significant differences for all arms and all adoption indicators. The results are robust to Benjamini-Hochberg False Discovery Rate corrections for multiple hypothesis testing.

Very few households in rural Rwanda engage in ‘stove stacking’, a phenomenon observed in many countries in the Global South that refers to the use of multiple stoves. In the control group, households have on average 1.1 usable stoves in their house, and regularly use only 1.02 stoves. The EEBC mainly replaces “three-stone stoves” and traditional round mud stoves (see Figure 4). If we look only at households that regularly use the EEBC (Figure 4 – B), we see that stove stacking after receiving the EEBC is most prominent in the no subsidy arm with almost 25% of households using other stoves in addition to the new EEBC. In most households, the EEBC replaced traditional stoves completely.[31]

A - All households **B - Only EEBC users**

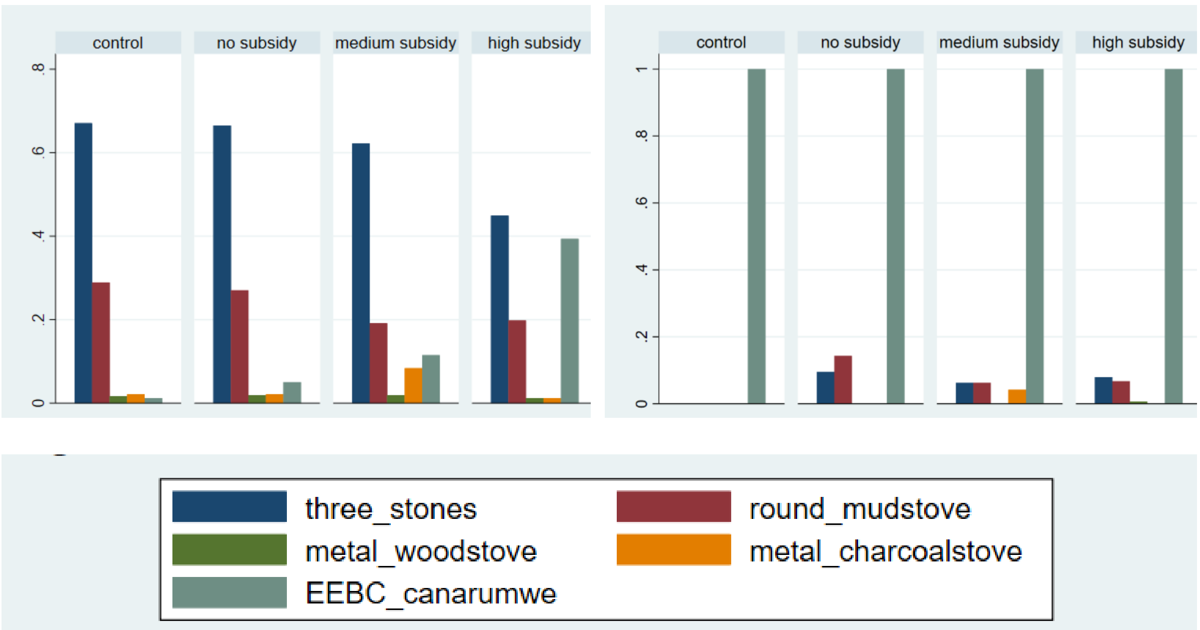

Figure 4: Share of household using different stoves in a typical week

4.2. *Impacts*

We evaluate impacts at two levels: the village level and household level (distinguishing between adopters and non-adopters). Since adoption is not random, we use an out-of-sample propensity score matching approach to identify comparable households from control villages.[32] As specified in the PAP, we regress the impact indicators on the different treatment

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[31] We speculate that this difference may be due to non-random selection. In the no subsidy arm, mainly relatively “richer” households adopt, who eat “more dishes” per meal and therefore need more stoves.
[32] See Appendix 2 for more details on the matching approach.

intensities and cluster the standard errors at the village level. We control for household and village level characteristics as robustness checks (see Section 3.2 for more details).

4.2.1. Fuel switching

Before turning to our main results, we consider fuel switching.[33] In the theoretical model we adopted the simplifying assumption that branches, twigs, and residue are perfect substitutes. In our empirical context, households carefully mix these components, depending on availability and stove characteristics. For example, the EEBC combustion chamber has only few air inlets, and sufficient draft for clean combustion is only achieved if bigger chunks of wood are used. Our installers encouraged households to use branches with the EEBC even though it can also be used with twigs.

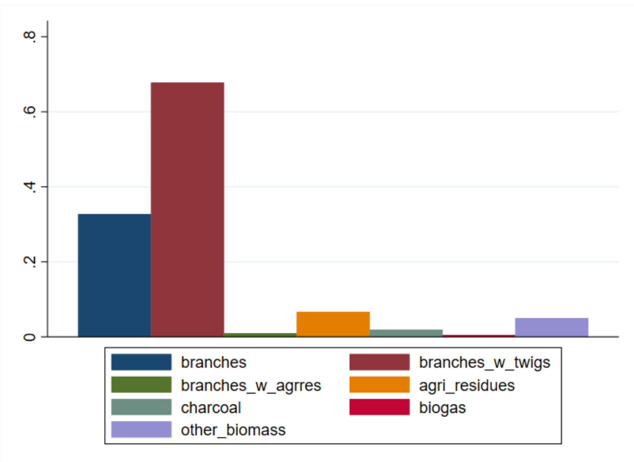

Figure 5: Share of households using respective fuel (only control arm)

We asked households about the fuel mix they use (see Figure 5). Most households in the control group use branches or branches mixed with twigs and sprigs. Agricultural residues and other biomass such as leaves and reed are used only to a small extend. Charcoal is hardly used at all. If we now look at changes due to the usage of the EEBC, we observe that households switch to branches (at the extensive margin) and reduce their use of branches

[33] In the PAP, we did not specify that we would investigate fuel switching between different types of firewood (i.e. twigs and branches). Only analyses for the overall amount of firewood were pre-specified.

mixed with twigs and sprigs (see Figure 6). This is in line with expectations as the EEBC runs best with branches.

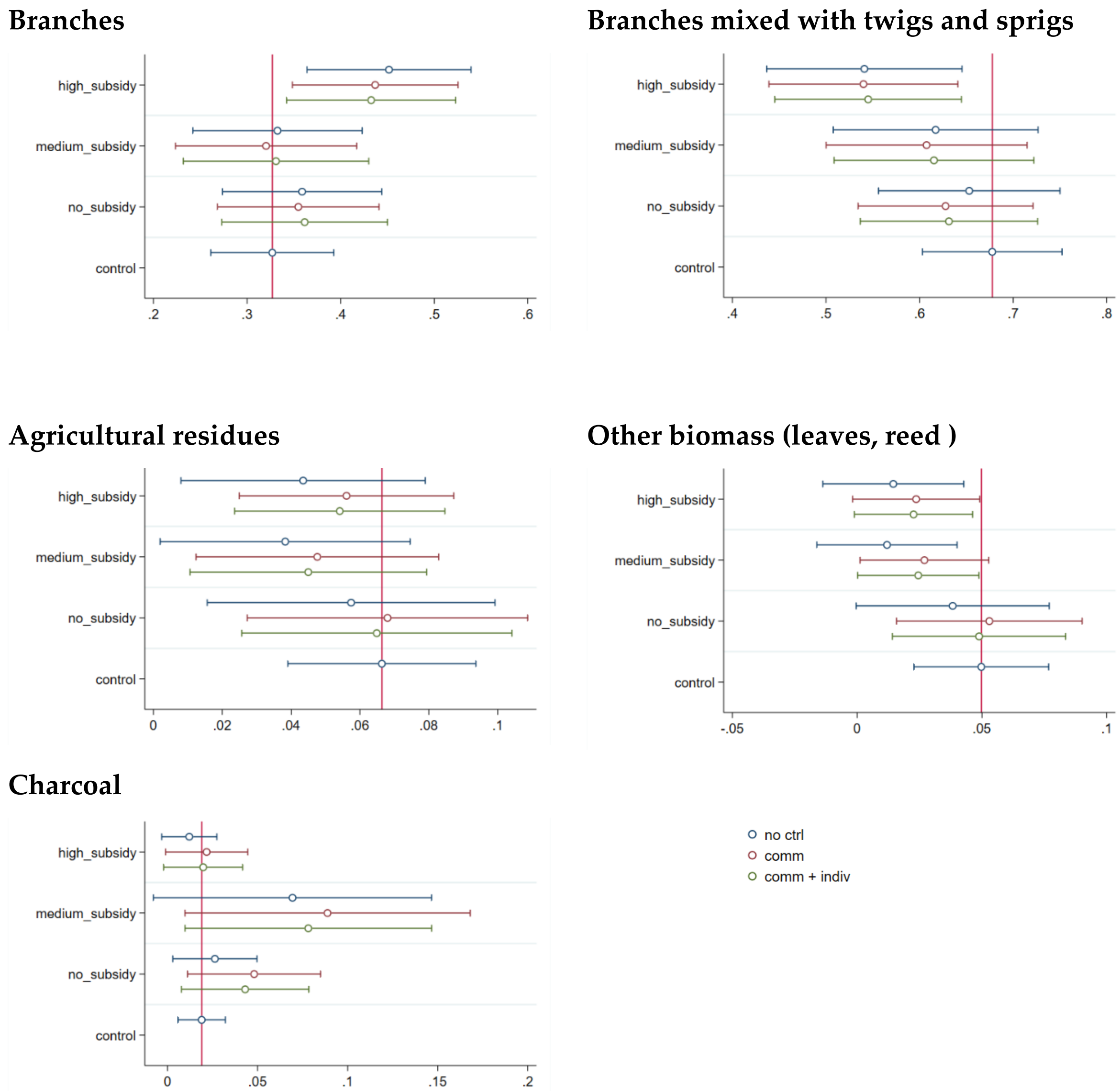

Figure 6: Impact of treatment on fuel use (extensive margin) – Share of HH using respective fuel

Notes: treatment coefficients against the control arm (red line represents the mean of the control arm). 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

4.2.2. Fuel consumption

The total amount of firewood clearly decreases with the use of the EEBC (Figure 7). This is the first order effect induced by the stove. Yet, this aggregate result masks some heterogeneity across fuel mixes. Since many EEBC adopters switch towards branches, the overall amount of branches consumed roughly stays the same. The consumption of branches mixed with twigs and sprigs decreases.[34]

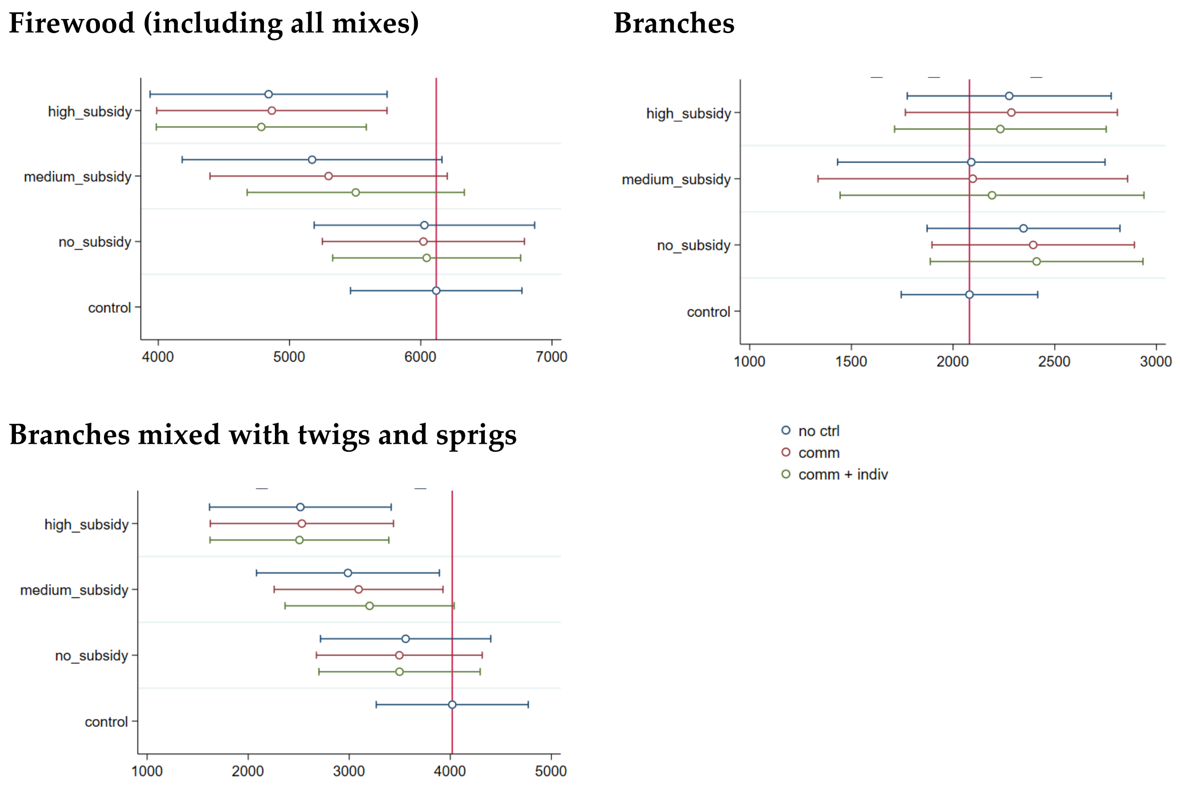

Figure 7: Impact on village level on fuel use (intensive margin) – Amount of fuel used last cooking day in grams

Notes: The graph displays the treatment coefficients against the control arm (red line represents the mean of the control arm). 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

[34] These results are robust to Benjamini-Hochberg (1995) False Discovery Rate corrections in order to account for multiple hypotheses testing. The disaggregated analysis for the different fuel mixes was not pre-specified in the PAP.

We next turn to an investigation of the existence of the local macro rebound effects. If this effect exists, then higher EEBC saturation should reduce firewood consumption among EEBC adopters. We observe a net reduction in wood consumption, capturing the direct effect and possibly a micro rebound effect. The macro rebound occurs if there is extra firewood consumption by non-adopters in treatment villages (compared to the control arm), reflecting lower prices or greater wood abundance *in situ* (lower collection cost). Indeed, adopters reduce consumption of firewood—the reduced form effect capturing the sum of the technological and micro-rebound effect is consistently negative (see Figure 8)[35]. However, we find no indication of a macro rebound effect. Comparing the three levels of EEBC saturation, there is no substantial difference across the three arms. If anything, non-adopters seem to reduce wood consumption (but the effect we measure is far from statistically significant)

Total amount of firewood (all mixes)

Adopter **Non-Adopter**

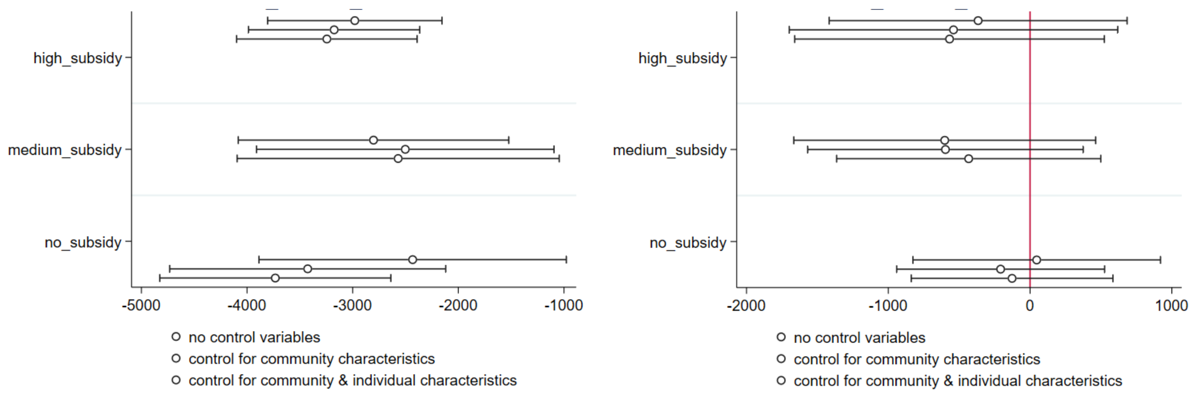

Figure 8: Impact by adopters and non-adopters: fuel use (intensive margin) – Amount of fuel used last cooking day in grams

Notes: Sample sizes for adopters are small: high subsidy arm: n=156; medium subsidy arm: n=47; no subsidy n=21. The graph display the treatment coefficients against the control arm. 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

[35] The effect is robust to Benjamini-Hochberg (1995) False Discovery Rate corrections in order to account for multiple hypotheses testing.

4.2.3. Monetary fuel prices

We now consider the local macro rebound effect from another direction. A precondition for macro rebounds is that local scarcity of firewood and firewood prices are affected by EEBC saturation leading to lower firewood prices. We elicit monetary firewood prices in the household survey and at the village level. Power to detect impacts based on the household sample is low since only 186 households in our sample buy branches, and only 105 households buy branches mixed with twigs and sprigs (see also Section 5 for a discussion of ex-post power). This equals 30% of users of branches and only 10% of users of the mix of branches with twigs. Moreover, the price variable is measured with noise since firewood prices are normally set at the "bundle level", and bundle size varies over villages, regions, and time. Households therefore state the price per bundle and estimate the weight of the bundle, enabling us to calculate the price per kilogram. We use the same procedure for prices elicited at the village level, but here a "typical bundle" is also weighted by enumerators using a hand scale. To account for seasonality of firewood prices, we elicit the minimum and the maximum price over the last year.

Overall, we see a borderline significant reduction of prices per kg of branches mixed with twigs and sprigs but no effect on prices for branches (see Figure 9). This is consistent with earlier results, since adoption decreases only consumption of branches mixed with twigs and sprigs. The result for the mix of branches with twigs and sprigs is, however, not robust. When controlling for village and household characteristics, the treatment effect turns insignificant.[36] As highlighted above, one explanation for the lack of clear effects is the small share of firewood users that buy firewood.

We see a slight tendency towards lower prices in the high subsidy arm when looking at yearly peak prices for branches elicited at the village level (see Figure 10). Again, the effect is not robust to alternative specifications. Note that at the village level we did not differentiate between different types of firewood, and have information on the price of branches only.

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[36] The original price variable exhibits some extremely high and low prices that are substantially higher/lower than prices that can be observed in villages. This is why we top- and bottom-code the variable at the 5% and 95% percentile. This is in contrast to what we specified in the pre-analysis plan, namely, to cap the price variables only at the 99th percentile. If we cap the price variable at the 99th percentile, results turn insignificant for both pure firewood and firewood mixed with twigs.

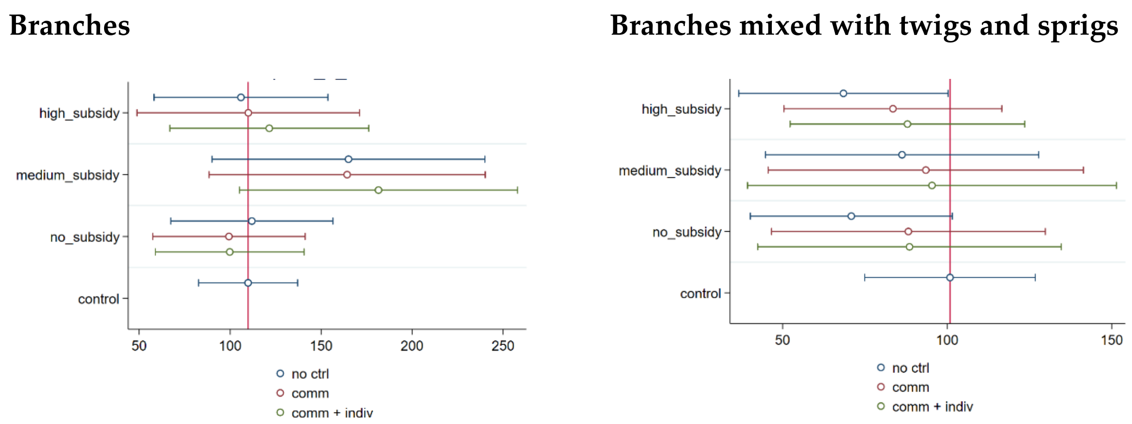


Figure 9: Price per kg of fuel (from HH survey)

Notes: The graph displays the treatment coefficients against the control arm (red line represents the mean of the control arm). 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

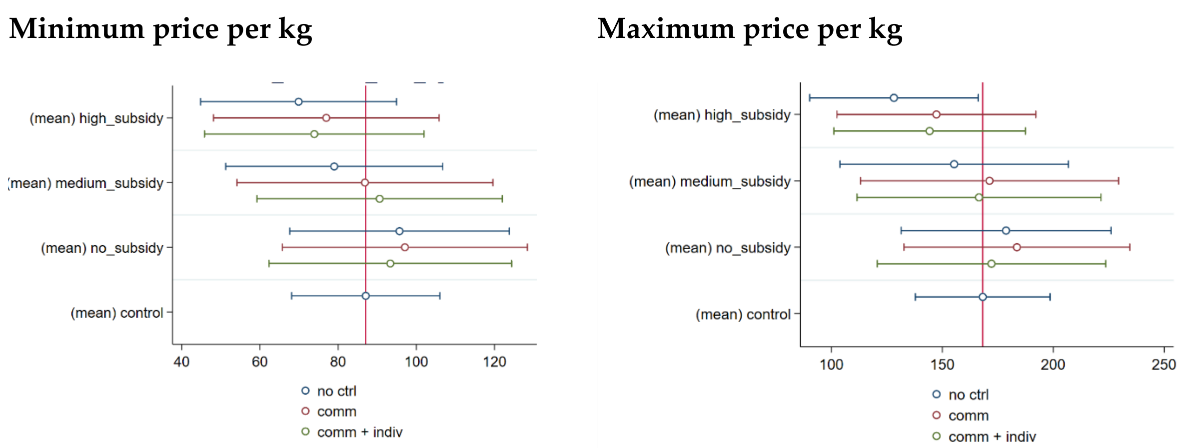


Figure 10: price per kg of branches (from village survey)

Notes: treatment coefficients against the control arm (red line represents the mean of the control arm). 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

4.2.4. Fuel collection time

Since only a small share of households in rural Rwanda buys firewood, we also look at fuel collection time as a measure for the costs associated with collecting wood. If a local macro rebound effect exists, higher EEBC saturation should reduce collection time because firewood is more abundantly available. We consider overall collection time per month, reflecting both fuelwood availability and the amount of firewood a household consumes (which, for EEBC adopters, is also affected by higher stove efficiency). Additionally, we look at collection time per unit of firewood, which should more clearly indicate fuelwood availability, but is also noisier since it combines two imprecise variables. For this indicator, we restrict the sample to households that only collect wood (n=1380), since for households that collect and buy we do not know how much of the consumed firewood is collected.[37]

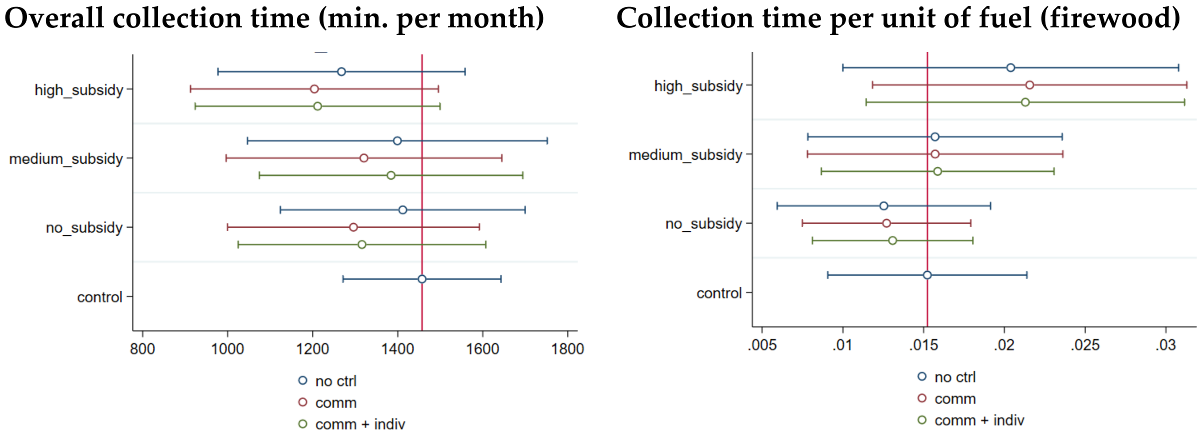


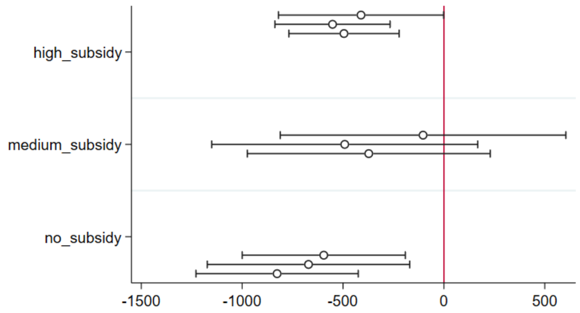
Figure 11: Impact on village level - fuel collection time (min. per months /per unit of fuel)

Notes: treatment coefficients against the control arm (red line represents the mean of the control arm). 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

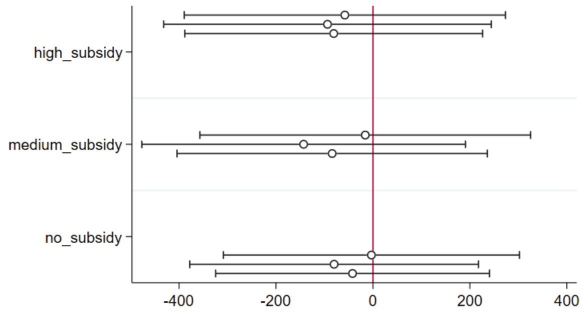
[37] The impact indicator collection time per unit of firewood is not pre-specified in our PAP. We added this indicator, since it measures fuelwood availability more clearly. Dropping this indicator does not change our main conclusions.

Overall collection time (minutes per months)

Adopters

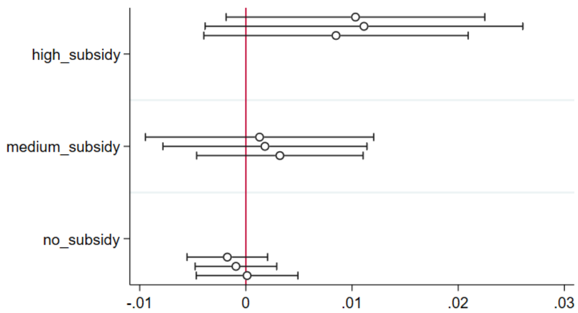


Non-Adopters

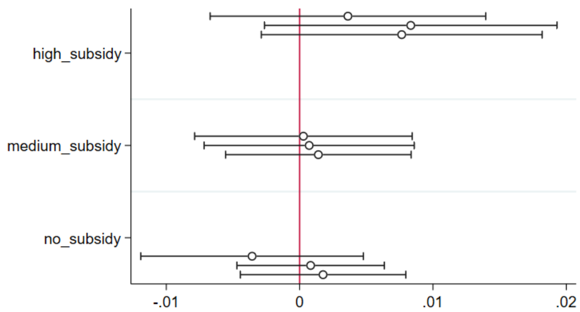


Collection time per unit of firewood

Adopters



Non-Adopters



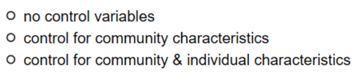


Figure 12: Impact by adopters and non-adopters: fuel collection time

Notes: Sample sizes for adopters are small: high subsidy arm: n=156; medium subsidy arm: n=47; no subsidy n=21. The graph display the treatment coefficients against the control arm. 90% confidence interval. Std. Errors clustered at village level. Complete regression results can be found in Appendix 3. No ctrl: no control variables; comm: control only for village characteristics (c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community); comm+ ind: controls additionally for individual characteristics (chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport)

Households dedicate around 1,400 minutes per month to collecting firewood, or some 45 minutes per day. EEBC adopters in the high and no subsidy arm reduce this time by more than one-third (see Figure 11). In the medium subsidy arm, we do not observe any clear effect. Importantly, non-adopters do not change their overall collection time, so there is no indication for a local macro rebound effect (see Figure 12). Looking at the collection time per unit of firewood, non-adopting households in the high subsidy arm appear to increase their collection time per unit of firewood, but the difference is statistically insignificant at conventional levels (p-value 0.14).

Post-hoc qualitative analysis revealed that the reason for this is that firewood collection in rural Rwanda is typically tied to other activities, like agricultural work, attending school, or moving around in pursuit of household activities. For example, household members collect branches and twigs after tending their plots and carry the biomass home afterwards. Similarly, school children may carry firewood when walking home from school. The daily collection time of 45 minutes includes a sizable *fixed cost* component—the time involved in walking home from the plot or school. Our qualitative analysis revealed that marginal cost of collecting firewood, or the time actually spent searching for an additional unit of firewood, is therefore lower than expected. This explains why collection time per unit increases when less biomass is needed, and why overall collection time is not very responsive to modest changes in demand for fuel.

5. Discussion

Subsidizing improved stoves promotes adoption, and adoption of improved stoves reduces firewood consumption. However, we do not find robust evidence of impacts on local biomass markets—fuelwood prices are rather stable, and fuelwood collection time by non-adopters is essentially unaffected. Also, firewood consumption by non-adopters does not increase. The macro rebound refers to quantity adjustments in demand after a change in local scarcity and prices. Why don't we find evidence of such a local macro-rebound? Several potential explanations exist for the absence of a measurable macro-rebound, and we probe the main ones in this section. We distinguish between explanations arguing against the existence of macro rebounds in our context, and explanations based on our inability to identify them.

5.1 Macro rebounds do exist, but cannot be measured

Our first possible explanation for why we fail to capture a macro rebound is based on peculiarities of the production function of firewood in Rwanda. In our theoretical model, households allocate time to produce crops, biomass or other goods. However, and as mentioned above, households allocate very little time to firewood collection as a *separate task*. Instead, households collect biomass for cooking while walking home—after working in the fields, or after school. In other words, we may think about crop production and biomass collection as joint production.[38] While some households will collect smaller quantities of firewood after adopting an improved stove, the consequences for collection effort of other households will be relatively small. If firewood collection involves relatively low marginal (effort) cost, then our ability to pick up the macro rebound effect of improved stoves is compromised. In other words, while actual wood consumption by non-adopters may increase, we might fail to notice it by observing wood prices or collection times. However, we do not believe that this explanation is valid. We do not only consider effects on price and collection time, but also consider impacts on wood consumption by non-adopters directly. According to results summarized in Figure 8, firewood consumption by non-adopters is unaffected by the introduction of EEBCs. Indeed, several of our point estimates are of the opposite sign. Low marginal effort costs of gathering firewood do not explain our results.

Next is the concern of low statistical power. Two factors explain why power is lower than desirable. Market-level pilot analyses are almost inevitably based on a relatively small number of clusters, and we were unable to measure prices and collection time with great precision.[39] A relatively small number of clusters not only introduces the risk of a type II error,

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[38] Formalization of this idea is simple. If crops and fuel are jointly produced then l_b=0. This implies households will always allocate share α of their time to production of other goods and services and share (1-α) to the production of crops and fuel. This allocation is independent of the efficiency of cookstoves, and general equilibrium effects do not occur (a consequence of Cobb-Douglas utility). The only effect of reducing demand for branches is that the forest stock will increase, so that it is easier for (non-adopting) households to collect the quantity of biomass they need. This may imply, for example, that they can collect wood closer to their homes and have to carry the biomass over shorter distances. These are subtle effects we are unable to detect with our empirical analysis.

[39] Only a small subsample of households buys firewood. Moreover, firewood markets are informal and price information is hard to elicit accurately. Firewood prices are set at the bundle level and bundle size varies over villages, regions, and time. For prices elicited at the household level, enumerators ask for the price per bundle and estimate together with the responding household the weight of a typical bundle. The price per kg is calculated subsequently. At the village level, the typical bundle size is additionally weighted by the enumerators with a hand scale. In comparison to other studies using a

it also increases the risk of spurious results—driven by chance. Table 2 reports the results of an ex-post power analysis for changes in prices and fuelwood collection time. We are adequately powered to pick up reductions in prices and collection time of 30%-60% (with outliers up to around 100%), depending on the indicator chosen. However, the minimum detectable effect size (MDE) for firewood consumption by non-adopters compares favorably to these outcomes. We are powered to pick up treatment effects of a magnitude of 20-30% of the control group's mean, which may be close to the effect size that matters from a policy making perspective. Nevertheless, the concern of a small sample remains. Burke et al (2019) study an intervention at the level of Kenyan maize markets, and conclude: "*This exercise should be interpreted as an illustration of how GE effects can shape the distribution of welfare gains in isolated markets, rather than precise quantitative estimates*" (p.834). A similar caveat is relevant for the current study.

Table 2: Ex-post power calculations (Minimum Detectable Effect Size)

	Control mean	MDE as % of control mean			observed effect size as % of control mean		
		no subsidy	med subsidy	high subsidy	no subsidy	med subsidy	high subsidy
price kg branches	109.83	0.65	1.02	0.61	-0.4	0.50	0.02
price kg branches mixed with twigs and sprigs	100.87	0.47	0.61	0.45	-0.32	-0.14	-0.30
min price branches (village level)	87.05	0.43	0.48	0.48	-0.20	-0.09	0.10
max price branches (village level)	168.2	0.34	0.46	0.42	-0.24	-0.08	0.06
overall collection time	1457	0.30	0.36	0.30	-0.13	-0.04	-0.03
time per unit collected	0.02	0.98	0.82	0.66	0.33	0.00	-0.20
Total consumption of firewood among non-adopters		0.26	0.27	0.21	-0.06	-0.10	0.01

5.2 Macro rebound effects of efficient stoves do not exist in rural Rwanda

It could also be the case that our failure to identify macro rebounds is due to the fact that they simply do not exist. If so, the first possible explanation for why macro rebound may not exist is based on market integration. Our level of randomization is the *umudugudu*, to

random saturation designs to study local general equilibrium effects the number of villages included in our sample is rather high. Per treatment arm, we surveyed 21 villages (i.e. price points).

which we refer to as the village. Often two or three of these entities form one settlement cluster. *Umudugudu* firewood markets may sometimes be connected within one cluster, which would dilute our treatment effect as excess firewood from treatment villages could be collected or bought by households of other *umudugudus* in the cluster. While we cannot rule-out such *within*-settlement trade, broader *inter*-settlement trade is unlikely for two reasons. First, qualitative research revealed that transaction costs associated with hauling piles of wood from one place to the next are large enough to prevent firewood export to other settlement clusters.[40] Second, the great majority of households collects their own firewood, and can only be indirectly affected by inter-settlement trade (through changes in the local abundance of firewood). The share of households trading fuelwood on the market seems too small to matter for local firewood abundance. Hence, market integration at the settlement level might dilute our treatment, but since regional markets are not integrated, we dismiss the explanation that market integration prevents macro rebound effects to emerge.[41]

A second potential explanation follows directly from the theoretical model. If initially the system is in a steady state characterized by elastic supply, then quantities harvested can be adjusted downwards with minimal effects on local prices. Considering the bioeconomic equilibria discussed in the context of Figure 2, this amounts to steady states like A where the supply curve is flat. Steady state A, however, corresponds to the case where the natural vegetation is near its carrying capacity level, or where very little extraction occurs. This is not the relevant case to describe rural Rwanda. Population densities are high, and the natural vegetation is intensively exploited by villagers. Bailis et al. (2015) estimate the fraction of non-renewable biomass (fNRB) for fuel harvesting in pan-tropical areas and estimate that the fNRB

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[40] Our results are also not affected by changes in charcoal trade emerging in response to price differentials. While charcoal is traded across greater distances—reflecting charcoal's greater value per kg of produce—we did not detect charcoal flows adjusting to our intervention. Charcoal consumption in the control group is very low (2 percent or 8 households). The share of charcoal users is similarly low in the high subsidy and no subsidy arm. It is only slightly higher in the medium subsidy arm (6 percent or 29 households). The higher share of charcoal users in medium subsidy villages seems to be unrelated to our intervention. First, our intervention would lower the use of charcoal if firewood became cheaper due to the intervention. Second, only five households acquired a charcoal stove after 2015, when our intervention started. The imbalance between the arms accordingly existed at baseline already.

[41] Essentially this is also an argument about statistical power. If local firewood markets are integrated at the settlement level, then our intervention may be too small to yield a response that can be detected given our sample size. If firewood markets are integrated in regional markets then the supply of wood is perfectly elastic and rebound effects should not occur.

is more than 50% in Rwanda. This is substantially higher than in other world-regions, where the average fNRB amounts to only around 30%. Steady state D therefore more accurately describes the situation in Rwanda than steady state A. However, the price elasticity of supply in steady state D is low. Hence, we also do not believe that this candidate explanation is relevant for our context.

A final and more promising explanation for the absence of macro rebounds is based on the production function of food, combined with overall land scarcity in rural Rwanda. While the adoption of efficient stoves may increase the local abundance of firewood, non-adopters have no use for extra firewood *unless they can also increase production of crops*—recall that crops and energy are complements in the production of food. Because of the high population density in rural Rwanda, however, virtually all land suitable for cultivation is already in use. The scope for expanding crop production is very small, so rebound effects are unlikely to materialize.

Our overall interpretation is that macro rebounds seem unimportant for the context we study, presumably because of constraints on the production of crops – complements to energy in the production of food. However, we acknowledge that our empirical analysis is under-powered to identify small or modest impacts at the local market level. This is an important caveat, which can only be addressed in more ambitious future studies encompassing many more villages.

6. Conclusion

We theoretically analyzed micro and macro rebound effects of energy efficient biomass cookstoves in a low-income country and used a cluster randomized saturation design to empirically study the macro rebound in Rwanda. This is the first paper to study macro rebounds empirically, using an experimental approach. After demonstrating variation in adoption rates across experimental arms, we found a reduction in firewood consumption among adopters, but no evidence of a macro rebound. Specifically, neither prices, collection time nor wood consumption by non-adopters was significantly affected by the adoption rate of improved stoves. The main policy implication is that energy-efficiency gains observed at the individual level can be extrapolated to determine the welfare effects of interventions aiming to increase energy efficiency.

However, we caution against generalizing this proof-of-concept regarding the absence of local macro rebound effects to other settings. While our results may be representative for densely populated rural areas as the countryside of Rwanda, it is not evident that these insights spill over to other regions in Africa. Our theoretical model emphasizes the importance of context for the nature of rebounds—both the sign and the magnitude—and from our empirical analysis and qualitative observations we take away that specifics of production functions matter greatly for the type of outcomes that eventuate. Whether or not macro rebounds occur depends on several considerations, so the impact of interventions to promote energy efficiency are likely to vary from one country to the next.

First, we demonstrate theoretically that the intensity of woodfuel extraction vis-à-vis biomass production is important. The biomass supply curve is backward bending, reflecting a concave biological growth function. Biomass extraction beyond the maximum sustainable yield level implies that standing tree stocks will be depleted. Price increases will stimulate extraction effort, but eventually result in lower (steady state) extraction levels. Depending on whether the forest is nearly pristine or heavily disturbed, the introduction of energy efficient stoves causes different types of effects. A particularly dramatic macro rebound effect may occur for depleted tree stocks, on the backward bending part of the supply curve. Energy savings by EEBCs may "flip" the bioeconomic equilibrium from one steady state to another—with greater biomass, lower prices and greater extraction levels. A pre-condition for such effects to occur is the open access nature of the forest base. Hence, understanding macro rebounds requires studying the interaction between the ecological production base and the institutional context (property rights).[42]

Second, local macro rebounds only occur on fragmented local markets—else changes in the availability of relative biomass will simply result in changes in inter-village energy trade. This condition is satisfied for our setting. A minority of households purchases firewood, and transport costs are high as people do not have access to trucks and carts are rare. Firewood is mostly carried. This might be different in other settings. As a rule of thumb, the higher the

[42] In settings with clearly assigned property rights or very effective forest management systems, overexploitation would be circumvented, and the supply curve would be completely upward sloping. Such a more textbook-like supply curve could lead to more traditional macro rebounds, if tree owners are able to increase their supply of firewood on local markets.

share of purchased fuels are, the likelier biomass markets are to be integrated. For example, for regions in which mostly charcoal is used, a fuel that is produced to be transported, local macro rebound effects are unlikely to emerge unless the EEBC are introduced across the entire charcoal market.

Third, in very poor and land-scarce settings like ours, biomass may not be the binding constraint for increasing food consumption. Crops and biomass are complements in the production of food, but crop markets are imperfect (people mainly consume their own harvest) and the cropping area cannot be expanded. Households also face difficulty when trying to increase their yield through the application of modern inputs like fertilizer. In the absence of opportunities to obtain additional crops to eat, demand for energy among non-adopters is price inelastic and does not increase. While a macro rebound will not occur in our setting, outcomes may be different in locations where production of crops can be expanded or where markets for food crop are better developed.

Beyond the local macro rebound effect, our findings on adoption add to a growing literature on the price responsiveness of demand for improved cookstoves. From this perspective, they are more than a proof-of-concept. Improved cookstoves that are well-adapted to local cooking habits are likely to be used intensely, even when subsidized or freely distributed (see Bensch and Peters 2020, Bluffstone et al. 2021, Pattanayak et al. 2019), while stoves that require changes in cooking behavior or substantial maintenance are often not well adopted (e.g., Hanna et al. 2016, Mortimer et al. 2017). We also observe that adoption lowers fuel consumption, which confirms previous studies on well-adapted improved cookstoves (see Bensch and Peters 2015, La Fave et al. 2021). In countries like Rwanda, therefore, policy could usefully dedicate more resources to foster energy efficiency as this seems to offer double-dividend potentials—poverty alleviation and environmental benefits, including climate change mitigation.

7. References

Alem, Y., (2021). *Mitigating climate change through sustainable technology adoption: Insights from cookstove interventions*. No. 907. Ruhr Economic Papers.

Allcott, H., & Greenstone, M. (2012). Is there an energy efficiency gap? *Journal of Economic Perspectives*, *26*(1), 3-28.

Akram, A. A., Chowdhury, S., & Mobarak, A. M. (2017). *Effects of emigration on rural labor markets* (No. w23929). National Bureau of Economic Research.

Baid, S. J.A. Bohren, C. McIntosh, and B. Özler (2018). Optimal design of experiments in the presence of interference, *The Review of Economics and Statistics*, 100(5): 844-860.

Bailis, R., R. Drigo, A. Ghilardi, and O. Masera (2015). The carbon footprint of traditional woodfuels. *Nature Climate Change* 5, 266-272.

Bensch, G. and J. Peters (2015). 'The intensive margin of technology adoption – experimental evidence on improved cooking stoves in rural Senegal', *Journal of Health Economics* **42**: 44–63

Bensch, G. and J. Peters (2020). "One-off subsidies and long-run adoption—Experimental evidence on improved cooking stoves in Senegal", *American Journal of Agricultural Economics*, 102(1), 72-90.

Bensch, G., M. Grimm, and J. Peters (2015). 'Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso', *Journal of Economic Behavior & Organization* **116**: 187–205.

Bensch, G., M. Jeuland, and J. Peters (2021). 'Efficient biomass cooking in Africa for climate change mitigation and development', *One Earth*, forthcoming.

Berkouwer, S. B., & Dean, J. T. (2021). Credit, attention, and externalities in the adoption of energy efficient technologies.

Bluffstone, R., A. Beyene, Z. Gebreegziabher, P. Martinsson, A. Mekonnen, and F. Vieider (2021). Does providing improved biomass cooking stoves free-of-charge reduce regular usage? Do use incentives promote habits?. *Land Economics*, In Press

Brooks, N., V. Bhojvaid, M.A. Jeuland, J.J. Lewis, O. Patange, and S.K. Pattanayak (2016). 'How much do alternative cookstoves reduce biomass fuel use? Evidence from North India', *Resource and Energy Economics* **43**: 153–171.

Burke, M., L. Bergquist and E. Miguel (2019). Sell low and buy high: Arbitrage and local price effects in Kenyan markets. *The Quarterly Journal of Economics* 134: 785-842

Carranza, E. and R. Meeks (2020). Energy efficiency and electricity reliability. *Review of Economics and Statistics* **103**: 1-15

Chan, N. W., & K. Gillingham (2015). The microeconomic theory of the rebound effect and its welfare implications. *Journal of the Association of Environmental and Resource Economists*, *2*(1), 133-159.

Clark, C. (1990). *Mathematical bioeconomics*, 2nd edition. New York: Wiley Interscience

Cohen, J. and P. Dupas (2010). Free distribution or cost sharing? Evidence from a randomized malaria experiment. *The Quarterly Journal of Economics* 125: 1-45

Cunha, J. M., G. De Giorgi, & S. Jayachandran (2019). The price effects of cash versus in-kind transfers. *The Review of Economic Studies*, *86*(1), 240-281.

Davis, Lucas (2008). Durable goods and residential demand for energy and water: Evidence from a field trial. *RAND Journal of Economics* 39 (2): 530–46.

Davis, Lucas, Alan Fuchs, and Paul Gertler (2014). Cash for coolers: Evaluating a large-scale appliance replacement program in Mexico. *American Economic Journal: Economic Policy*, 6 (4), 207-38.

Egger, D., J. Haushofer, E. Miguel, P. Niehaus, and M. W. Walker (2019). *General equilibrium effects of cash transfers: experimental evidence from Kenya* (No. w26600). National Bureau of Economic Research.

Fowlie, M. and Meeks, R., 2021. Rethinking Energy Efficiency in the Developing World. *Review of Environmental Economics and Policy*, 15 (2), 238-260.

Fowlie, M., Greenstone, M., & Wolfram, C. (2018). Do energy efficiency investments deliver? Evidence from the weatherization assistance program. *The Quarterly Journal of Economics*, *133*(3), 1597-1644.

Frondel, M., Peters, J., & Vance, C. (2008). Identifying the rebound: evidence from a German household panel. *The Energy Journal*, *29*(4).

Gebreegziabher, Z, A. D. Beyene, R. Bluffstone, P. Martinsson, A. Mekonnen and"M. A. Toman (2018). "Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia", *Resource and Energy Economics*, 52, 173-185.

Gerarden, T. D., R. G. Newell, and R. N. Stavins (2017). Assessing the energy-efficiency gap. *Journal of Economic Literature*, *55*(4), 1486-1525.

Gillingham, K. (2014). Identifying the elasticity of driving: evidence from a gasoline price shock in California, *Regional Science and Urban Economics*, 13-24.

Gillingham, K., D. Rapson, and G. Wagner (2016). The Rebound Effect and Energy Efficiency Policy. *Review of Environmental Economics and Policy, 10 (1),* 68–88.

Hanna, R., E. Duflo, and M. Greenstone (2016). 'Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves', American Economic Journal: Economic Policy 8(1): 80–114.

International Energy Association (2019). World Energy Outlook 2019.

Jetter, J., Y. Zhao, K.R. Smith, B. Khan, T. Yelverton, P. DeCarlo, and M.D. Hays 2012. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environmental Science & Technology* 46(19): 10827-10834.

Jones, D. W. (1988). Some simple economics of improved cookstove programs in developing countries. *Resources and Energy*, *10*(3), 247-264.

LaFave, D., A.D. Beyene, R. Bluffstone, S.T. Dissanayake, Z. Gebreegziabher, A. Mekonnen and M. Toman, 2021. Impacts of improved biomass cookstoves on child and adult health: Experimental evidence from rural Ethiopia. *World Development*, *140*, p.105332.

Lenz, L., A. Munyehirwe, J. Peters, and M. Sievert 2017. Does large-scale infrastructure investment alleviate poverty? Impacts of Rwanda's electricity access roll-out program. *World Development*, 89, pp.88-110.

Levine, D. I., T. Beltramo, G. Blalock, C. Cotterman, and A. M. Simons (2018). What impedes efficient adoption of products? Evidence from randomized sales offers for fuel-efficient cookstoves in Uganda. *Journal of the European Economic Association*, *16*(6), 1850-1880.

Martin II., W. J., R. I. Glass, J.M. Balbus and F.S. Collins (2011). A major environmental cause of death. *Science*, 334(6053): 180-181.

Mobarak, A.M., P. Dwivedi, R. Bailis, L. Hildemann and G. Miller (2012). Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences*, *109*(27), pp.10815-10820.

Mortimer, K., C.B. Ndamala, A.W. Naunje, J. Malava, C. Katundu, W. Weston, ... and S.B. Gordon (2017). A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *The Lancet*, *389*(10065), 167-175.

Muralidharan, K., and V. Sundararaman (2015). The aggregate effect of school choice: Evidence from a two-stage experiment in India. *The Quarterly Journal of Economics*, *130*(3), 1011-1066.

Muralidharan, K., Niehaus, P., and Sukhtankar (2017). *General equilibrium effects of (improving) public employment programs: Experimental evidence from india* (No. w23838). National Bureau of Economic Research.

Pattanayak, S. K., M. Jeuland, J. J. Lewis and F. Usmani, N. Brooks, V. Bhojvaid, A. Kar, L. Lipinski, L. Morrison, O. Patange and N" Ramanathan (2019). "Experimental evidence on promotion of electric and improv"d biomass cookstoves", *Proceedings of the National Academy of Sciences*. DOI: 10.1073/pnas.1808827166.

Rosa, G., F. Majorin, S. Boisson, C. Barstow, M. Johnson, M. Kirby, F. Ngabo, E. Thomas, and T. Clasen. (2014). Assessing the impact of water filters and improved cook stoves on drinking water quality and household air pollution: a randomised controlled trial in Rwanda. *PloS one* 9.3: e91011.

Shankar, A.V., A.K. Quinn, K.L. Dickinson, K.N. Williams, O. Masera, D. Charron, D. Jack, J. Hyman, A. Pillarisetti, R. Bailis, and P. Kumar (2020). Everybody stacks: Lessons from household energy case studies to inform design principles for clean energy transitions. *Energy Policy*, *141*, p.111468.

UN-General Assembly, 2015. Resolution adopted by the General Assembly on 25 September 2015. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

WHO, 2016. Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. World Health Organization, Geneva.

Zein-Elabdin, E. O. (1997). Improved stoves in Sub-Saharan Africa: the case of the Sudan. *Energy Economics*, *19*(4), 465-475.

APPENDICES

Appendix 1: Twigs as a source of biomass

How do the long-term outcomes change when villagers collect twigs, rather than cut branches? Assume that cutting branches involves social or legal costs, so that all biomass collection is based on the collection of twigs from the forest floor. This means the natural forest will be at carrying capacity level, *R*=*K*. Again, define a Schaefer-type production function: $b = vXl_b$. Villagers are indifferent between producing crops, other goods and services, and biomass, hence the unit price of biomass is given by $p_b = 1/vX$. We assume that a constant fraction γ of the forest dies in each time period (generating a flow of harvestable twigs equal to γK), and that a constant fraction μ of the twig stock is lost due to natural decay so is no longer available as source of biomass. This implies the following equation of motion for the flow of biomass:

$$\frac{dX}{dt} = \gamma K - \mu X - b \qquad \text{(A1)}$$

In a steady state, $b = \gamma K - \mu X$. Substituting $X = 1/vp_b$ in this expression yields the steady state supply curve:

$$p_b = \frac{\mu}{v(\gamma K - b)}. \qquad \text{(A2)}$$

We can analyze the comparative statics by combining (14) and (A2). Both curves are drawn in Figure 2. Increasing energy efficiency, again, implies that the demand curve D shifts down. This means a twig-based biomass system moves to a new long-term equilibrium, characterized as follows:

Proposition A1*. In the long term, after the twig stock X has reached a new steady state, the introduction of an EEBC (with $\theta' > \theta$) will have the following effects.*

A. *EEBC will not affect the production, consumption or prices of other goods and services;*
B. *Improved stoves will induce villagers to re-allocate some of their labor from biomass collection to crop production ($l_b \downarrow, l_c \uparrow$), which will …*
C. *… leave the steady state forest stock unaffected (R=K) and …*
D. *… increase production and consumption of crops ($c \uparrow$), effective energy ($\theta b \uparrow$), and food ($f \uparrow$);*
E. *EEBC will unambiguously reduce biomass harvested ($b \downarrow$); and*

F. EEBC will reduce the relative price of biomass.

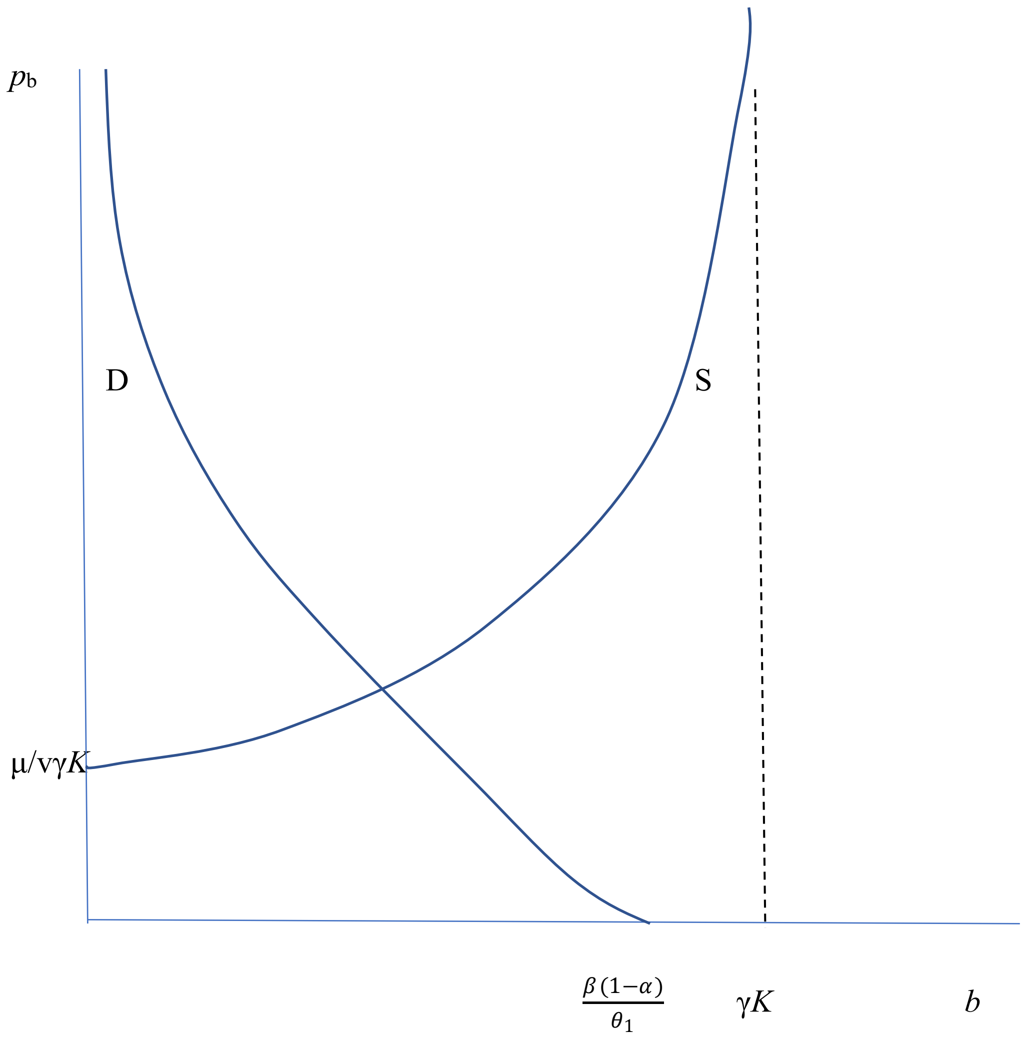


Figure A1: Demand for twigs and supply of twigs

The most complex case to consider is the one where households may switch back-and-forth between collecting twigs and cutting branches. The two biomass extraction production functions are linear in labor, so villagers specialize in the activity that generates most biomass per unit of labor. From (8): households specialize in collecting twigs if $vX>qR$, and they specialize in cutting branches if $vX<qR$.

It is possible to characterize the long-term equilibrium more precisely, assuming we start with a virgin forest stock ($R=K$) and associated twig stock ($X=\gamma K/\mu$). First, there may be contexts where demand for biomass is low and it is easy to collect twigs. Harvesting branches is typically subject to some form of regulation, and possibly sanctioning. If social or legal costs are associated with harvesting live branches, then villagers have to take precautions to avoid getting caught, and parameter q will be low ($vX>qR$). Under such conditions, households only collect twigs, so $R=K$ and $b=\frac{\beta(1-\alpha)vX}{\beta+vX\theta}$. In the absence of harvesting branches, we can solve for the steady state twig stock by solving $\frac{dX}{dt}=0$, or:

$$\gamma K-\mu X=\frac{\beta(1-\alpha)vX}{\beta+vX\theta}: \tag{A3}$$

Denote the relevant solution by X^*.[43] If $vX^*>qK$, then harvesting from live biomass will never start, and the steady state is as described above.

Conversely, consider the case of a pristine forest where cutting branches is an easy and low-cost activity (so that $vX<qK$). Harvesting branches draws down the forest stock (slowing down the flow of branches as a side effect). In the absence of harvesting twigs, we can solve for the steady state forest stock by solving $\frac{dR}{dt}=0$, or:

$$rR\left(1-\frac{R}{K}\right)=\frac{\beta(1-\alpha)qR}{\beta+qR\theta}. \tag{A4}$$

Denote the relevant solution by R^*.[44] If $qR^*>vX^{**}$ (where X^{**} is the steady state twig stock in the absence of twig collection, defined as $X^{**}=\gamma R^*/\mu$), then harvesting from twigs will never start, and the steady state is as described in section 2.4.

More complex dynamics emerge when:

$$qR^*<vX^*<vX^{**}<qK. \tag{19}$$

In this case, the long-term steady state is characterized by "cycles", caused by villagers switching between the extraction of twigs and branches. As the forest and twig stock move in opposite directions, the comparative statics are described by the analyses in sections 2.4 and the Annex above, depending on relative abundance of the two biomass types.

[43] Observe that a quadratic equation emerges, so there are two solutions of X. The relevant solution, when starting from a pristine forest, is the one that is closest to the pristine steady state twig stock ($X=\gamma K/\mu$) from below.
[44] Here, too, two solutions for R emerge. The relevant one is the largest one, closest to K. This is the steady state that occurs first when the virgin forest stock is drawn down.

Appendix: Identification of hypothetical EEBC adopters

In the first step we estimate a probit model including only households from the treatment villages and regress EEBC adoption status of a household on a number of covariates. We do this for each treatment arm separately. Results are displayed in the first column of Figure A2_1 below. In a second step, we use the coefficients from this regression to predict the probability to adopt, both among the treatment villages and among the control villages (see Figure A2_2).

With these probabilities, also known as the propensity scores, we perform a radius caliper matching approach to identify among control villages those households that are most comparable to households that adopted the EEBC in treatment villages. We use all control households with propensity scores within a radius of 0.02 around the propensity score of a treatment household as counterfactual. Normalized weights are assigned to control households to account for the frequency a control household is chosen as a counterfactual.

Figure A2_1: Probit estimations before and after matching

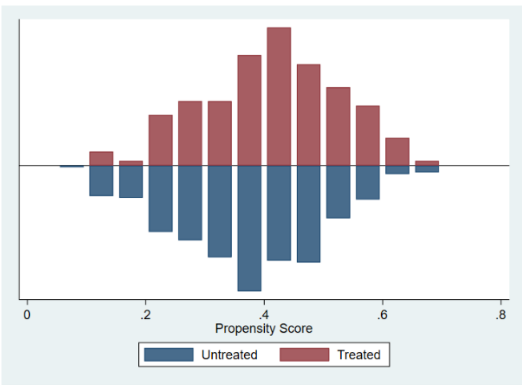
Adopters vs.	HIGH non-adopter in high subsidy comm	all HH in control comm	radius_matched	MEDIUM non-adopter in medium subsidy comm	all HH in control comm	radius_matched	NO non-adopter in no subsidy comm	all HH in control comm	radius_matched
VARIABLES									
hdum kitchen BAS	0.505	0.172	-0.147	-0.002	-0.066	-0.049	-0.246	-0.391	-0.190
	(0.006)***	(0.281)	(0.423)	(0.994)	(0.748)	(0.855)	(0.385)	(0.124)	(0.642)
chef literate	-0.126	-0.180	-0.127	0.225	0.079	-0.062	0.087	0.159	0.284
	(0.379)	(0.150)	(0.338)	(0.236)	(0.655)	(0.777)	(0.755)	(0.523)	(0.449)
chef sexe	-0.210	-0.111	-0.043	-0.023	-0.021	-0.022	0.686	0.627	0.182
	(0.214)	(0.464)	(0.792)	(0.913)	(0.915)	(0.927)	(0.014)*	(0.011)*	(0.622)
chef age	-0.008	-0.002	0.004	0.002	-0.000	-0.001	-0.003	0.001	0.008
	(0.108)	(0.657)	(0.431)	(0.805)	(0.991)	(0.930)	(0.739)	(0.898)	(0.513)
hdum ICS BAS	0.048	0.030	-0.004	0.016	-0.012	0.004	0.148	0.103	0.024
	(0.264)	(0.432)	(0.917)	(0.778)	(0.823)	(0.953)	(0.039)*	(0.133)	(0.812)
hh size	-0.051	-0.098	-0.075	-0.291	-0.328	-0.201	0.226	0.173	-0.063
	(0.709)	(0.415)	(0.559)	(0.112)	(0.063)*	(0.350)	(0.341)	(0.435)	(0.846)
walls	0.258	0.364	0.265	0.166	0.129	0.079	0.206	-0.072	-0.306
	(0.189)	(0.035)*	(0.138)	(0.521)	(0.613)	(0.797)	(0.530)	(0.821)	(0.454)
soil	-0.201	-0.151	-0.020	-0.388	-0.335	0.020	-0.339	-0.242	-0.046
	(0.250)	(0.306)	(0.899)	(0.094)*	(0.120)	(0.938)	(0.279)	(0.392)	(0.908)
hh dum kid2 6	0.143	0.168	0.082	0.241	0.187	-0.058	0.080	-0.017	0.009
	(0.387)	(0.281)	(0.628)	(0.289)	(0.382)	(0.829)	(0.803)	(0.954)	(0.984)
hh dum kid6 15	-0.249	-0.135	0.021	0.415	0.273	-0.159	0.103	0.034	-0.093
	(0.201)	(0.409)	(0.904)	(0.095)*	(0.225)	(0.577)	(0.739)	(0.907)	(0.825)
hh dum kid u2	-0.071	-0.129	-0.241	-0.402	0.247	0.398	0.899	0.714	0.215
	(0.825)	(0.634)	(0.408)	(0.220)	(0.482)	(0.361)	(0.015)*	(0.034)*	(0.580)
hdum el BASELINE	0.460	0.118	-0.050	-0.684	-0.428	0.112	-0.525	-0.514	0.188
	(0.190)	(0.654)	(0.856)	(0.148)	(0.384)	(0.863)	(0.351)	(0.373)	(0.770)
plantation	-0.074	0.331	0.392	0.111	0.333	0.335	-0.092	0.215	0.366
	(0.607)	(0.012)*	(0.004)*	(0.548)	(0.065)*	(0.123)	(0.723)	(0.377)	(0.297)
hdum paid f BAS	0.006	0.313	0.309	-0.220	0.037	0.060	0.606	0.575	0.032
	(0.969)	(0.026)*	(0.038)*	(0.307)	(0.862)	(0.812)	(0.016)*	(0.011)*	(0.925)
Constant	-0.399	-0.835	-0.166	-1.439	-1.187	0.125	-2.618	-2.357	-0.599
	(0.307)	(0.010)*	(0.637)	(0.005)***	(0.007)*	(0.820)	(0.000)*	(0.000)*	(0.513)
Observations	413	578	578	417	469	457	418	443	428
Pseudo R-squared	0.0449	0.0416	0.0285	0.0575	0.0469	0.0211	0.152	0.125	0.0337
chi-square test	24.57	28.55	17.71	16.88	15.52	5.593	25.36	25.39	3.719
Prob > chi2	0.0391	0.0120	0.221	0.262	0.343	0.976	0.0312	0.0309	0.997
R-squared									

Covariates

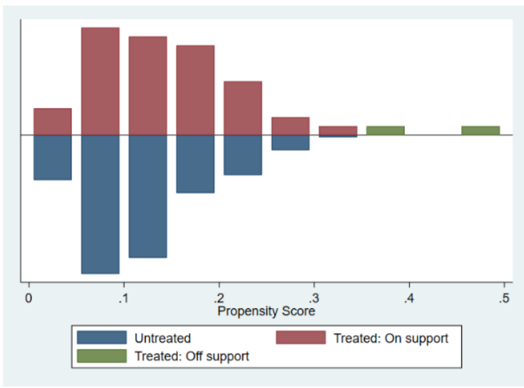
kitchen_baseline:	=1 if separate kitchen (=0 outside or cooking in living room)
chef_literate:	=1 if hoh visited at least alphabetisation courses
chef_sexe:	=1 if hoh is female
chef_age :	Hoh's age
hdum_knowICS_BAS:	HH dummy - had known EEBC at baseline (before April)
hh_size :	number of household members including children
walls :	wall material is better than wood or clay/mud
soil :	soil material is better than earth
hh_dum_kid2_6	HH dummy: children 2-6 years in HH
hh_dum_kid6_15	HH dummy: children 6-15 years in HH
hh_dum_kid_u2	HH dummy: children 0-2 years in HH
hdum_el_BA	HH dummy - had electricity connection at baseline
plantation	HH dummy – has tree plantations on their fields
hh_dum_paid_f_BAS	HH dummy- any female household member pursued remunerated income generating activ

Figure A2_2: Radius matching: Distribution of propensity scores among adopters in treatment villages ("treated") and all HHs in control villages ("untreated")

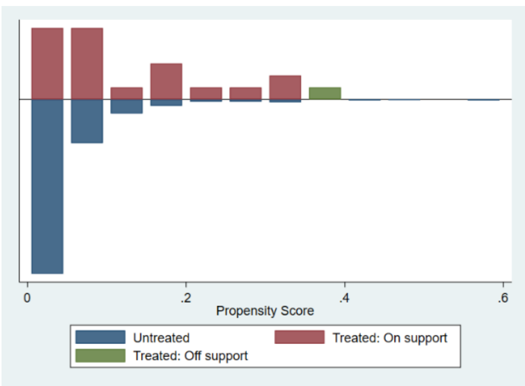
High subsidy



Medium subsidy



No subsidy



To assess whether the comparability of the groups has improved by identifying the hypothetical stove adopters, we provide standard balancing test provided by STATA (pstest). As first step, we analyse differences in means on the covariates between the connected households and the control households. As can be seen in Figures A2_3a to A2_3b, the difference between the groups to be compared becomes substantially smaller if we use the hypothetical adopters within the control villages as counterfactual instead of all households in the control villages. For some covariates, however, substantial imbalance remains (high subsidy treatment: “plantation” “soil” “hdum_ICS_BAS”) or balance also gets worse (high subsidy treatment: “chef_age”).

As a second way to test the quality of the matching process, we look at the pseudo-R^2 of the probit model, regressing the adoption status on covariates used for the matching. First, we use all HH in the control villages as counterfactual (see Figure A2_4, “unmatched”) and then we use only the hypothetical adopters (Figure A2_4, “matched”). The pseudo-R^2 is expected to fall if a balance improvement is achieved. This is what we see in our data: the pseudo-R^2 falls. Furthermore, the respective chi-squared statistic shows a joint significant influence of the covariates in the non-matched case and no joint significant influence in the matched case.

Figure A2_3a: Balancing of covariates between high subsidy treatment and control group (differences in means)

Variable	Unmatched / Matched	Mean Treated	Mean Control	%bias	%reduct |bias|	t-test t	t-test p>|t|	V(T)/ V(C)
hdum_kitchen_BAS	U	.88462	.79384	24.9		2.52	0.012	.
	M	.88462	.87979	1.3	94.7	0.13	0.895	.
chef_literate	U	.5641	.5782	-2.8		-0.30	0.761	.
	M	.5641	.59374	-6.0	-110.3	-0.53	0.597	.
chef_sexe	U	.19872	.26303	-15.3		-1.60	0.111	.
	M	.19872	.20263	-0.9	93.9	-0.09	0.932	.
chef_age	U	48.699	48.346	2.3		0.25	0.805	0.90
	M	48.699	46.84	12.4	-427.0	1.12	0.262	1.01
hh_size	U	5.3013	4.9692	15.7		1.66	0.097	0.95
	M	5.3013	5.2786	1.1	93.2	0.10	0.924	1.01
walls	U	.42308	.42891	-1.2		-0.13	0.900	.
	M	.42308	.44127	-3.7	-212.0	-0.32	0.747	.
soil	U	.19231	.11137	22.6		2.55	0.011	.
	M	.19231	.14723	12.6	44.3	1.06	0.290	.
hh_dum_kid2_6	U	.44872	.48815	-7.9		-0.84	0.400	.
	M	.44872	.48816	-7.9	-0.0	-0.70	0.487	.
hh_dum_kid6_15	U	.76923	.68483	19.0		1.98	0.048	.
	M	.76923	.75524	3.1	83.4	0.29	0.773	.
hh_dum_kid_u2	U	.21795	.26777	-11.6		-1.22	0.223	.
	M	.21795	.24344	-5.9	48.8	-0.53	0.595	.
hdum_el_BASELINE	U	.04487	.04976	-2.3		-0.24	0.808	.
	M	.04487	.05625	-5.3	-132.6	-0.46	0.648	.
hdum_paid_f_BAS	U	.05128	.05213	-0.4		-0.04	0.967	.
	M	.05128	.06861	-7.8	-1937.0	-0.64	0.521	.
plantation	U	.33974	.22275	26.2		2.88	0.004	.
	M	.33974	.22452	25.8	1.5	2.27	0.024	.
hdum_ICS_BAS	U	.24359	.16588	19.3		2.13	0.033	.
	M	.24359	.16469	19.6	-1.5	1.73	0.084	.

Notes: * if variance ratio outside [0.73; 1.37] for U and [0.73; 1.37] for M
The standardised % bias is the % difference of the sample means in the treated and non-treated (full or matched) sub-samples as a percentage of the square root of the average of the sample variances in the treated and non-treated groups (formulae from Rosenbaum and Rubin, 1985); V(T)/V(C): the variance ratio (for continuous covariates) of treated over non-treated. This ratio should equal 1 if there is perfect balance.

Figure A2_3b: Balancing of covariates between medium subsidy treatment and control group (differences in means)

Variable	Unmatched / Matched	Mean Treated	Mean Control	%bias	%reduct |bias|	t-test t	t-test p>|t|	V(T)/V(C)
hdum_kitchen_BAS	U	.82979	.79384	9.2		0.58	0.562	.
	M	.82222	.81659	1.4	84.3	0.07	0.945	.
chef_literate	U	.6383	.5782	12.3		0.79	0.429	.
	M	.62222	.63294	-2.2	82.2	-0.10	0.917	.
chef_sexe	U	.25532	.26303	-1.8		-0.11	0.909	.
	M	.26667	.24504	4.9	-180.4	0.23	0.817	.
chef_age	U	48.702	48.346	2.4		0.15	0.879	0.79
	M	49.044	48.298	5.1	-109.6	0.24	0.810	0.82
hh_size	U	5.0213	4.9692	2.4		0.16	0.875	1.04
	M	5.0222	5.1272	-4.8	-101.6	-0.23	0.820	1.10
walls	U	.31915	.42891	-22.7		-1.45	0.148	.
	M	.33333	.38283	-10.2	54.9	-0.48	0.629	.
soil	U	.17021	.11137	16.9		1.19	0.235	.
	M	.15556	.12641	8.4	50.5	0.39	0.695	.
hh_dum_kid2_6	U	.38298	.48815	-21.2		-1.37	0.172	.
	M	.4	.44068	-8.2	61.3	-0.39	0.700	.
hh_dum_kid6_15	U	.74468	.68483	13.2		0.84	0.401	.
	M	.73333	.74302	-2.1	83.8	-0.10	0.918	.
hh_dum_kid_u2	U	.2766	.26777	2.0		0.13	0.897	.
	M	.24444	.29621	-11.6	-486.7	-0.55	0.585	.
hdum_el_BASELINE	U	.06383	.04976	6.0		0.41	0.679	.
	M	.06667	.03554	13.4	-121.3	0.66	0.508	.
hdum_paid_f_BAS	U	.02128	.05213	-16.4		-0.93	0.354	.
	M	.02222	.02028	1.0	93.7	0.06	0.950	.
plantation	U	.38298	.22275	35.2		2.45	0.014	.
	M	.35556	.24917	23.4	33.6	1.09	0.277	.
hdum_ICS_BAS	U	.17021	.16588	1.2		0.08	0.940	.
	M	.17778	.14868	7.7	-571.1	0.37	0.713	.

Notes: * if variance ratio outside [0.73; 1.37] for U and [0.73; 1.37] for M
The standardised % bias is the % difference of the sample means in the treated and non-treated (full or matched) sub-samples as a percentage of the square root of the average of the sample variances in the treated and non-treated groups (formulae from Rosenbaum and Rubin, 1985); V(T)/V(C): the variance ratio (for continuous covariates) of treated over non-treated. This ratio should equal 1 if there is perfect balance.

Figure A2_3c: Balancing of covariates between no subsidy treatment and control group (differences in means)

Variable	Unmatched / Matched	Mean Treated	Mean Control	%bias	%reduct |bias|	t-test t	t-test p>|t|	V(T)/ V(C)
hdum_kitchen_BAS	U	.7619	.79384	-7.6		-0.35	0.725	.
	M	.8	.76401	8.5	-12.7	0.27	0.789	.
chef_literate	U	.71429	.5782	28.4		1.23	0.218	.
	M	.7	.67415	5.4	81.0	0.17	0.864	.
chef_sexe	U	.42857	.26303	34.8		1.67	0.096	.
	M	.4	.37208	5.9	83.1	0.18	0.861	.
chef_age	U	48.81	48.346	3.0		0.13	0.893	0.99
	M	49.25	47.045	14.3	-375.8	0.49	0.626	1.54
hh_size	U	5.7619	4.9692	34.4		1.64	0.101	1.30
	M	5.8	5.6097	8.3	76.0	0.26	0.800	1.30
walls	U	.61905	.42891	38.3		1.72	0.087	.
	M	.6	.59405	1.2	96.9	0.04	0.970	.
soil	U	.19048	.11137	21.9		1.11	0.269	.
	M	.2	.23946	-10.9	50.1	-0.29	0.770	.
hh_dum_kid2_6	U	.42857	.48815	-11.8		-0.53	0.595	.
	M	.45	.48872	-7.7	35.0	-0.24	0.812	.
hh_dum_kid6_15	U	.80952	.68483	28.7		1.21	0.229	.
	M	.8	.80147	-0.3	98.8	-0.01	0.991	.
hh_dum_kid_u2	U	.2381	.26777	-6.7		-0.30	0.765	.
	M	.25	.31345	-14.4	-113.8	-0.44	0.665	.
hdum_el_BASELINE	U	.19048	.04976	43.5		2.74	0.006	.
	M	.2	.18522	4.6	89.5	0.12	0.909	.
hdum_paid_f_BAS	U	.04762	.05213	-2.0		-0.09	0.928	.
	M	.05	.03183	8.2	-302.5	0.28	0.779	.
plantation	U	.28571	.22275	14.3		0.67	0.502	.
	M	.3	.19371	24.1	-68.8	0.77	0.449	.
hdum_ICS_BAS	U	.38095	.16588	48.9		2.54	0.011	.
	M	.35	.35132	-0.3	99.4	-0.01	0.993	.

Notes: * if variance ratio outside [0.73; 1.37] for U and [0.73; 1.37] for M
The standardised % bias is the % difference of the sample means in the treated and non-treated (full or matched) sub-samples as a percentage of the square root of the average of the sample variances in the treated and non-treated groups (formulae from Rosenbaum and Rubin, 1985); V(T)/V(C): the variance ratio (for continuous covariates) of treated over non-treated. This ratio should equal 1 if there is perfect balance.

Figure A2_4a: Balancing of covariates between high subsidy treatment and control group (joint distribution)

Sample	Ps R2	LR chi2	p>chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.046	31.31	0.005	12.2	13.4	53.2*	1.06	0
Matched	0.028	11.95	0.610	8.1	6.0	39.5*	0.99	0

Notes: Mean and median bias as summary indicators of the distribution of the abs(bias); Rubins' B (the absolute standardized difference of the means of the linear index of the propensity score in the treated and (matched) non-treated group) and Rubin's R (the ratio of treated to (matched) non-treated variances of the propensity score index). Rubin (2001) recommends that B be less than 25 and that R be between 0.5 and 2 for the samples to be considered sufficiently balanced. An asterisk is displayed next to B and R values that fall outside those limits; %Var: the percentage of continuous variables that have variance ratios that exceed the 2.5th and 97.5th percentiles of the F-distribution

Figure A2_4b: Balancing of covariates between high subsidy treatment and control group (joint distribution)

Sample	Ps R2	LR chi2	p>chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.042	12.97	0.529	11.6	10.7	53.7*	1.33	0
Matched	0.019	2.37	1.000	7.5	6.4	32.3*	1.05	0

Notes: Mean and median bias as summary indicators of the distribution of the abs(bias); Rubins' B (the absolute standardized difference of the means of the linear index of the propensity score in the treated and (matched) non-treated group) and Rubin's R (the ratio of treated to (matched) non-treated variances of the propensity score index). Rubin (2001) recommends that B be less than 25 and that R be between 0.5 and 2 for the samples to be considered sufficiently balanced. An asterisk is displayed next to B and R values that fall outside those limits; %Var: the percentage of continuous variables that have variance ratios that exceed the 2.5th and 97.5th percentiles of the F-distribution

Figure A2_4c: Balancing of covariates between no subsidy treatment and control group (joint distribution)

Sample	Ps R2	LR chi2	p>chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.132	22.31	0.072	23.2	25.2	109.0*	1.16	0
Matched	0.025	1.41	1.000	8.2	8.0	37.1*	1.07	0

Notes: Mean and median bias as summary indicators of the distribution of the abs(bias); Rubins' B (the absolute standardized difference of the means of the linear index of the propensity score in the treated and (matched) non-treated group) and Rubin's R (the ratio of treated to (matched) non-treated variances of the propensity score index). Rubin (2001) recommends that B be less than 25 and that R be between 0.5 and 2 for the samples to be considered sufficiently balanced. An asterisk is displayed next to B and R values that fall outside those limits; %Var: the percentage of continuous variables that have variance ratios that exceed the 2.5th and 97.5th percentiles of the F-distribution

Appendix 3: Regression results

Details on Figure 6: Impact of treatment on fuel use (extensive margin) – Share of HH using respective fuel

VARIABLES	Branches			Branches with twigs			Agricultural Residues			Other biomass			Charcoal		
high_subsidy	0.125	0.110	0.106	-0.137	-0.138	-0.133	0.005	0.007	0.008	-0.035	-0.026	-0.027	-0.007	0.003	0.001
	(0.053)	(0.053)	(0.054)	(0.063)	(0.061)	(0.060)	(0.010)	(0.010)	(0.010)	(0.017)	(0.015)	(0.014)	(0.009)	(0.014)	(0.013)
medium_subsidy	0.006	-0.007	0.004	-0.061	-0.070	-0.062	0.014	0.017	0.018	-0.038	-0.023	-0.025	0.050	0.070	0.059
	(0.054)	(0.058)	(0.060)	(0.066)	(0.065)	(0.064)	(0.011)	(0.013)	(0.013)	(0.017)	(0.016)	(0.015)	(0.046)	(0.048)	(0.041)
no_subsidy	0.032	0.028	0.035	-0.025	-0.050	-0.046	0.024	0.027	0.028	-0.011	0.003	-0.001	0.007	0.029	0.024
	(0.051)	(0.052)	(0.053)	(0.058)	(0.056)	(0.057)	(0.015)	(0.015)	(0.015)	(0.023)	(0.022)	(0.021)	(0.014)	(0.022)	(0.021)
c_dist_route_princ		0.001	0.001		0.002	0.001		-0.001	-0.001		-0.001	-0.001		-0.001	-0.001
		(0.001)	(0.001)		(0.001)	(0.001)		(0.000)	(0.000)		(0.000)	(0.000)		(0.000)	(0.000)
c_inst_known		0.011	0.000		-0.016	-0.017		0.006	0.005		-0.018	-0.012		-0.029	-0.027
		(0.055)	(0.055)		(0.072)	(0.068)		(0.017)	(0.017)		(0.015)	(0.013)		(0.021)	(0.018)
c_publictransport_good		-0.060	-0.074		0.058	0.067		-0.007	-0.007		-0.024	-0.021		0.005	0.005
		(0.041)	(0.040)		(0.050)	(0.050)		(0.010)	(0.010)		(0.014)	(0.013)		(0.015)	(0.014)
c_mobilephonenetwork_good		0.068	0.059		-0.121	-0.107		0.005	0.007		0.014	0.010		0.044	0.034
		(0.039)	(0.037)		(0.042)	(0.041)		(0.010)	(0.011)		(0.014)	(0.013)		(0.021)	(0.018)
c_admin_office		0.031	0.032		-0.131	-0.120		0.007	0.012		0.001	-0.008		0.056	0.045
		(0.045)	(0.048)		(0.080)	(0.081)		(0.014)	(0.014)		(0.014)	(0.014)		(0.064)	(0.061)
c_school		0.070	0.079		0.029	0.009		-0.016	-0.016		0.021	0.021		-0.047	-0.033
		(0.038)	(0.038)		(0.054)	(0.051)		(0.010)	(0.011)		(0.013)	(0.013)		(0.037)	(0.031)
c_health		-0.175	-0.160		0.243	0.221		-0.021	-0.023		0.077	0.076		-0.012	0.002
		(0.059)	(0.058)		(0.087)	(0.081)		(0.013)	(0.013)		(0.056)	(0.055)		(0.037)	(0.032)
c_grid_el		0.005	0.002		-0.053	-0.040		0.008	0.009		-0.008	-0.009		0.039	0.027
		(0.037)	(0.039)		(0.048)	(0.049)		(0.011)	(0.010)		(0.010)	(0.010)		(0.023)	(0.018)
hh_size			0.004			0.004			-0.001			0.002			-0.003
			(0.006)			(0.006)			(0.002)			(0.002)			(0.002)
chef_literate			0.012			-0.032			0.001			0.000			0.002
			(0.026)			(0.023)			(0.006)			(0.010)			(0.007)
chef_age			0.001			-0.000			-0.000			-0.000			-0.001
			(0.001)			(0.001)			(0.000)			(0.000)			(0.000)
walls			0.005			-0.012			-0.014			0.029			0.015
			(0.031)			(0.036)			(0.012)			(0.010)			(0.011)
soil			0.040			-0.134			-0.008			-0.010			0.124
			(0.039)			(0.049)			(0.010)			(0.012)			(0.041)
goat_sheep			0.037			-0.013			0.004			-0.008			-0.023
			(0.028)			(0.029)			(0.010)			(0.009)			(0.007)
pig			0.042			0.019			-0.005			-0.007			-0.016
			(0.037)			(0.035)			(0.009)			(0.009)			(0.011)
cow			0.062			0.010			-0.000			-0.010			-0.018
			(0.029)			(0.030)			(0.007)			(0.009)			(0.008)
transport			0.087			-0.048			-0.004			0.000			-0.010
			(0.043)			(0.039)			(0.009)			(0.011)			(0.015)
Constant	0.327	0.281	0.137	0.678	0.732	0.751	0.009	0.018	0.042	0.050	0.052	0.046	0.019	-0.014	0.046
	(0.040)	(0.059)	(0.081)	(0.045)	(0.071)	(0.090)	(0.004)	(0.009)	(0.020)	(0.016)	(0.018)	(0.022)	(0.008)	(0.026)	(0.027)
Observations	1,672	1,672	1,671	1,672	1,672	1,671	1,672	1,672	1,671	1,672	1,672	1,671	1,672	1,672	1,671
Adjusted R-squared	0.009	0.021	0.033	0.010	0.040	0.048	0.002	0.005	0.004	0.007	0.020	0.024	0.014	0.082	0.149

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 7: Impact on village level on fuel use (intensive margin) – Amount of fuel used last cooking day in grams

VARIABLES	Firewood (including all mixes)			Branches			Branches with twigs and sprigs		
high_subsidy	-1,277.407	-1,252.916	-1,332.976	195.320	205.947	151.964	-1,503.210	-1,488.178	-1,512.532
	(542.849)	(527.702)	(481.014)	(301.436)	(313.375)	(312.771)	(540.191)	(545.108)	(532.091)
medium_subsidy	-946.078	-820.157	-613.430	8.898	16.284	110.825	-1,032.472	-926.705	-818.144
	(595.048)	(543.449)	(497.422)	(395.337)	(457.475)	(449.182)	(544.125)	(502.355)	(503.067)
no_subsidy	-90.310	-97.615	-72.785	265.711	313.284	330.118	-461.410	-523.889	-521.833
	(505.015)	(462.982)	(430.578)	(285.076)	(299.157)	(314.366)	(506.433)	(493.301)	(479.427)
c_dist_route_princ		30.443	24.735		18.140	16.043		14.016	10.586
		(9.847)	(9.828)		(5.945)	(6.447)		(7.704)	(7.730)
c_inst_known		-274.519	-357.397		-93.800	-137.477		-251.301	-285.311
		(518.868)	(419.008)		(356.560)	(324.180)		(467.324)	(432.485)
c_publictransport_good		-980.441	-1,017.193		-413.460	-479.557		-499.694	-463.667
		(423.266)	(392.998)		(286.145)	(275.662)		(329.141)	(327.660)
c_mobilephonenetwork_good		-483.276	-583.315		77.914	-86.739		-605.025	-547.403
		(393.799)	(356.956)		(290.548)	(261.186)		(359.764)	(356.364)
c_admin_office		-460.301	-566.930		357.915	243.997		-841.139	-841.668
		(593.866)	(527.931)		(313.768)	(331.764)		(478.659)	(467.520)
c_school		594.340	531.017		460.401	554.301		218.965	65.912
		(440.215)	(390.774)		(288.664)	(281.925)		(328.056)	(309.216)
c_health		573.385	628.334		-150.994	7.575		759.670	655.013
		(570.789)	(485.522)		(337.102)	(408.898)		(674.121)	(614.318)
c_grid_el		191.918	210.793		-50.514	-132.511		231.819	325.393
		(403.989)	(378.385)		(227.447)	(232.580)		(389.275)	(383.294)
hh_size			228.575			141.914			87.102
			(47.033)			(46.793)			(46.475)
chef_literate			336.909			229.420			168.841
			(215.047)			(199.865)			(232.411)
chef_age			14.968			13.922			2.887
			(7.248)			(6.842)			(7.922)
walls			463.537			352.526			132.639
			(327.875)			(282.964)			(265.465)
soil			-127.462			591.759			-691.707
			(397.317)			(420.643)			(352.672)
goat_sheep			805.330			214.099			542.672
			(259.217)			(222.251)			(248.787)
pig			260.107			2.204			234.417
			(284.075)			(247.735)			(296.530)
cow			1,195.288			776.973			422.558
			(264.595)			(232.977)			(221.017)
transport			90.871			726.120			-664.901
			(307.884)			(327.937)			(320.238)
Constant	6,118.088	6,056.385	3,121.200	2,080.820	1,735.791	-336.796	4,019.637	4,274.785	3,299.372
	(392.529)	(473.146)	(724.309)	(201.695)	(359.664)	(523.992)	(452.167)	(500.279)	(742.271)
Observations	1,672	1,672	1,671	1,672	1,672	1,671	1,672	1,672	1,671
Adjusted R-squared	0.011	0.039	0.080	-0.001	0.005	0.034	0.016	0.032	0.042

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 8: Impact by adopters and non-adopters: fuel use (intensive margin)

Amount of fuel used last cooking day in grams

VARIABLES	Non-Adopters: Firewood (including all mixes)			Non-Adopters: Firewood (including all mixes)			Non-Adopters: Firewood (including all mixes)		
high_subsidy	-366.351	-539.957	-567.927						
	(624.291)	(688.341)	(648.891)						
medium_subsidy				-601.774	-596.772	-432.946			
				(632.636)	(577.367)	(553.568)			
no_subsidy							46.951	-207.528	-126.917
							(518.916)	(435.770)	(422.736)
c_dist_route_princ		22.947	5.602		45.580	40.183		44.744	32.253
		(21.477)	(19.559)		(19.705)	(20.637)		(9.631)	(11.008)
c_inst_known		1,038.552	711.824		-365.582	-860.380		-2,135.814	-1,814.478
		(1,136.375)	(930.679)		(892.865)	(774.042)		(505.800)	(460.521)
c_publictransport_good		-1,666.509	-1,525.759		-777.642	-590.535		40.477	-466.438
		(667.767)	(596.497)		(886.562)	(907.424)		(496.868)	(454.372)
c_mobilephonenetwork_good		-361.109	-605.850		-500.471	-830.296		626.117	531.660
		(644.613)	(665.605)		(571.076)	(562.385)		(486.500)	(470.107)
c_admin_office		-493.886	-862.789		-957.525	-1,234.764		-1,358.359	-1,586.098
		(1,041.568)	(857.993)		(722.591)	(676.512)		(648.472)	(613.824)
c_school		314.430	322.434		630.814	474.268		-390.255	-662.088
		(797.969)	(711.230)		(624.019)	(606.967)		(458.144)	(424.566)
c_health		-74.900	68.733		235.338	350.074		-75.436	489.397
		(614.335)	(526.264)		(700.631)	(752.363)		(684.473)	(736.289)
c_grid_el		881.001	840.549		81.106	4.732		-144.575	15.647
		(750.025)	(675.221)		(891.353)	(928.121)		(579.772)	(510.963)
hh_size			192.405			287.438			223.190
			(77.981)			(53.640)			(86.397)
chef_literate			749.968			476.277			963.081
			(421.614)			(348.979)			(348.134)
chef_age			9.812			27.293			14.568
			(12.960)			(9.140)			(11.621)
walls			602.801			590.670			-587.693
			(632.284)			(524.668)			(444.323)
soil			71.294			-538.870			1,109.561
			(734.553)			(693.036)			(792.741)
goat_sheep			1,104.296			621.320			1,256.878
			(473.013)			(365.076)			(321.580)
pig			146.368			-378.023			298.585
			(336.228)			(504.430)			(435.007)
cow			1,736.997			824.214			741.182
			(499.130)			(431.337)			(374.860)
transport			-51.661			388.661			147.527
			(492.507)			(412.659)			(585.680)
Constant	6,037.950	6,039.921	3,219.723	5,960.880	5,829.354	2,403.936	6,073.925	5,394.185	2,692.260
	(385.085)	(617.454)	(1,073.006)	(378.416)	(614.926)	(832.702)	(404.100)	(493.548)	(1,062.577)
Observations	679	679	679	789	789	789	810	810	810
Adjusted R-squared	-0.000	0.022	0.079	0.002	0.037	0.065	-0.001	0.031	0.073

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 8: Impact by adopters and non-adopters: fuel use (intensive margin)

Amount of fuel used last cooking day in grams

VARIABLES	Adopters: Firewood (including all mixes)			Adopters: Firewood (including all mixes)			Adopters: Firewood (including all mixes)		
high_subsidy	-2,979.897	-3,175.630	-3,244.444						
	(490.321)	(481.549)	(507.589)						
medium_subsidy				-2,802.735	-2,502.199	-2,569.645			
				(757.660)	(833.301)	(902.333)			
no_subsidy							-2,432.378	-3,425.758	-3,732.530
							(859.657)	(771.819)	(646.164)
c_dist_route_princ		24.927	8.084		4.198	5.675		44.143	0.773
		(10.639)	(12.958)		(24.722)	(22.685)		(27.873)	(23.182)
c_inst_known		895.803	632.971		-1,919.096	-1,760.184		393.123	3,621.025
		(532.923)	(650.892)		(1,579.761)	(1,617.420)		(1,056.738)	(1,432.088)
c_publictransport_good		-1,289.981	-1,082.985		-988.463	-1,396.740		1,787.203	1,202.496
		(648.400)	(639.647)		(1,296.775)	(1,462.996)		(761.957)	(804.946)
c_mobilephonenetwork_good		367.291	287.026		168.296	312.061		1,623.540	1,940.835
		(547.846)	(594.247)		(705.963)	(772.459)		(635.491)	(575.372)
c_admin_office		-871.459	-1,247.064		-1,550.120	-1,323.523		-1,072.286	-1,633.822
		(883.321)	(744.358)		(1,105.598)	(1,208.417)		(642.939)	(780.894)
c_school		-345.762	-106.203		1,501.809	1,821.035		308.670	-527.301
		(559.697)	(519.269)		(1,217.307)	(1,409.144)		(1,051.325)	(643.547)
c_health		-1.222	-48.111		-1,023.243	-1,139.649		-1,884.248	-1,659.638
		(535.048)	(647.575)		(1,031.989)	(1,362.554)		(1,106.204)	(986.806)
c_grid_el		781.470	377.941		822.470	1,281.794		-512.227	267.574
		(685.175)	(675.491)		(1,566.641)	(1,784.310)		(878.338)	(640.291)
hh_size			191.248			186.854			499.091
			(66.762)			(76.620)			(162.005)
chef_literate			548.319			1,216.999			2,069.404
			(347.097)			(564.451)			(683.034)
chef_age			9.532			19.941			44.401
			(11.084)			(13.208)			(21.989)
walls			141.627			-543.729			-273.290
			(492.412)			(680.931)			(544.585)
soil			435.167			-74.650			-1,172.020
			(651.570)			(972.056)			(961.807)
goat_sheep			998.954			383.663			1,988.235
			(383.410)			(567.091)			(887.248)
pig			111.673			685.707			-718.405
			(387.657)			(664.309)			(871.028)
cow			925.793			-46.873			1,051.002
			(473.982)			(625.555)			(549.083)
transport			1,285.214			1,180.919			-358.132
			(494.435)			(848.691)			(1,076.037)
Constant	6,470.865	6,109.320	3,654.417	6,541.957	6,565.993	3,412.107	6,307.078	4,831.090	-1,575.043
	(421.865)	(400.472)	(861.248)	(527.627)	(711.645)	(1,249.418)	(551.127)	(815.914)	(1,871.247)
Observations	578	578	578	457	457	457	428	428	428
Adjusted R-squared	0.101	0.117	0.161	0.078	0.082	0.099	0.068	0.112	0.278

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 9: Price per kg of fuel (from HH survey)

VARIABLES	Price for Branches			Price for Branches mixed with twigs and sprigs		
high_subsidy	-3.910	0.117	11.648	-32.385	-17.352	-12.934
	(28.611)	(36.620)	(32.729)	(18.944)	(19.723)	(21.229)
medium_subsidy	55.170	54.431	71.653	-14.575	-7.353	-5.481
	(44.894)	(45.439)	(45.743)	(24.732)	(28.521)	(33.384)
no_subsidy	2.070	-10.521	-10.073	-29.995	-12.661	-12.316
	(26.681)	(25.075)	(24.470)	(18.283)	(24.791)	(27.459)
c_dist_route_princ		-0.348	-0.359		0.144	0.196
		(0.714)	(0.672)		(0.523)	(0.556)
c_inst_known		229.708	201.305		-5.240	9.222
		(111.525)	(107.875)		(31.754)	(28.274)
c_publictransport_good		-45.196	-46.445		-7.946	3.143
		(30.550)	(32.133)		(17.142)	(16.910)
c_mobilephonenetwork_good		38.094	23.416		10.169	-0.915
		(31.808)	(31.453)		(15.984)	(17.438)
c_admin_office		-32.359	-20.688		12.972	21.487
		(23.213)	(20.647)		(17.502)	(17.585)
c_school		-40.953	-32.421		2.835	-14.756
		(31.306)	(30.959)		(20.011)	(19.932)
c_health		59.849	46.881		25.163	34.454
		(50.970)	(45.924)		(42.343)	(47.630)
c_grid_el		11.768	9.250		-35.760	-46.238
		(29.980)	(26.499)		(13.925)	(17.005)
hh_size			-2.971			3.457
			(4.126)			(2.549)
chef_literate			30.168			21.083
			(21.202)			(17.449)
chef_age			-1.004			0.343
			(0.640)			(0.505)
walls			-33.374			-3.143
			(28.979)			(14.330)
soil			34.861			-32.293
			(42.354)			(15.757)
goat_sheep			-1.341			-25.308
			(19.270)			(11.684)
pig			-32.468			-16.403
			(27.861)			(18.512)
cow			17.322			-23.134
			(23.380)			(15.447)
transport			39.438			18.177
			(27.548)			(17.033)
Constant	109.830	110.400	156.142	100.867	91.713	71.710
	(16.293)	(30.594)	(50.734)	(15.432)	(25.235)	(43.390)
Observations	186	186	186	105	105	104
Adjusted R-squared	0.003	0.117	0.128	0.006	0.004	0.038

Notes: Robust standard errors clustered at village level in parentheses. Price variables are winzorized at the 95% level. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 10: Price per kg of branches (village survey)

VARIABLES	Maximum price per kg			Minimum price per kg		
high_subsidy	-40.013	-20.874	-23.939	-17.177	-10.105	-13.161
	(22.827)	(26.958)	(0.359)	(15.066)	(17.346)	(0.438)
medium_subsidy	-12.863	3.040	-1.672	-8.061	-0.215	3.560
	(30.956)	(34.970)	(0.960)	(16.694)	(19.687)	(0.851)
no_subsidy	10.521	15.404	3.942	8.642	10.022	6.283
	(28.461)	(30.608)	(0.899)	(16.885)	(18.849)	(0.737)
c_dist_route_princ		-0.024	-0.386		0.292	-0.030
		(0.633)	(0.559)		(0.313)	(0.926)
c_inst_known		-51.815	-47.782		-33.214	-34.689
		(19.099)	(0.065)*		(14.219)	(0.022)**
c_publictransport_good		-4.658	-10.229		5.106	-3.431
		(22.429)	(0.690)		(12.881)	(0.811)
c_mobilephonenetwork_good		-46.072	-48.954		-14.630	-13.353
		(22.239)	(0.062)*		(14.145)	(0.406)
c_admin_office		-10.086	-2.267		-6.486	-4.087
		(26.120)	(0.934)		(18.331)	(0.837)
c_school		-18.664	-15.402		-11.688	-11.690
		(17.507)	(0.501)		(11.096)	(0.395)
c_health		75.851	78.500		43.913	47.962
		(68.897)	(0.181)		(36.166)	(0.101)
c_grid_el		-39.364	-42.963		-18.840	-13.514
		(22.225)	(0.075)*		(13.337)	(0.367)
hh_size			-11.616			-11.432
			(0.616)			(0.446)
chef_literate			143.495			82.158
			(0.104)			(0.117)
chef_age			-3.128			-1.813
			(0.240)			(0.305)
walls			-15.706			5.685
			(0.643)			(0.782)
soil			10.498			-16.613
			(0.918)			(0.734)
goat_sheep			28.800			82.208
			(0.670)			(0.035)**
pig			173.860			91.441
			(0.010)**			(0.023)**
cow			-33.744			5.431
			(0.535)			(0.872)
transport			-52.706			-24.043
			(0.543)			(0.634)
c_total_population		0.004	-0.000		0.001	0.001
		(0.004)	(0.973)		(0.002)	(0.646)
Constant	168.200	205.277	337.225	87.049	94.407	152.559
	(18.255)	(35.974)	(0.015)**	(11.395)	(21.499)	(0.095)*
Observations	84	84	84	84	84	84
Adjusted R-squared	0.006	0.075	0.120	-0.003	0.008	0.079

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 11: Impacts on village level on fuel collection time (minutes per month/per unit of fuel)

VARIABLES	Overall collection time (min. per month)			Collectipn time per unit of fuel (firewood)		
high_subsidy	-189.378	-253.144	-245.529	0.005	0.006	0.006
	(174.731)	(175.268)	(173.142)	(0.006)	(0.006)	(0.006)
medium_subsidy	-57.956	-136.586	-72.844	0.000	0.000	0.001
	(211.906)	(194.917)	(186.309)	(0.005)	(0.005)	(0.004)
no_subsidy	-45.274	-161.212	-141.319	-0.003	-0.003	-0.002
	(173.010)	(178.058)	(175.045)	(0.004)	(0.003)	(0.003)
c_dist_route_princ		8.250	6.051		-0.000	-0.000
		(4.692)	(4.450)		(0.000)	(0.000)
c_inst_known		-7.152	-8.547		0.001	0.001
		(260.926)	(273.610)		(0.005)	(0.005)
c_publictransport_good		395.112	435.696		0.004	0.002
		(152.532)	(150.113)		(0.004)	(0.005)
c_mobilephonenetwork_good		-215.490	-136.210		-0.003	-0.001
		(128.569)	(123.623)		(0.004)	(0.004)
c_admin_office		-413.664	-334.550		0.002	0.004
		(191.836)	(178.160)		(0.008)	(0.008)
c_school		49.623	-93.068		-0.005	-0.008
		(215.592)	(219.563)		(0.004)	(0.004)
c_health		807.390	686.093		0.006	0.005
		(345.424)	(335.186)		(0.006)	(0.006)
c_grid_el		-216.478	-165.585		-0.005	-0.004
		(155.717)	(148.973)		(0.004)	(0.004)
hh_size			97.544			0.001
			(19.076)			(0.000)
chef_literate			-113.894			-0.002
			(90.876)			(0.002)
chef_age			-5.022			-0.000
			(2.401)			(0.000)
walls			-190.625			-0.006
			(97.618)			(0.003)
soil			-630.868			-0.008
			(117.222)			(0.002)
goat_sheep			130.070			0.005
			(75.205)			(0.004)
pig			110.394			0.003
			(118.577)			(0.006)
cow			39.965			-0.007
			(91.131)			(0.003)
transport			-456.696			-0.002
			(123.711)			(0.003)
Constant	1,457.073	1,439.946	1,366.239	0.015	0.020	0.022
	(111.646)	(193.431)	(227.789)	(0.004)	(0.005)	(0.006)
Observations	1,672	1,672	1,671	1,313	1,313	1,313
Adjusted R-squared	0.000	0.031	0.080	0.001	0.003	0.019

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 12: Impact by adopters and non-adopters: fuel collection time

VARIABLES	Adopters: Overall collection time			Adopters: Overall collection time			Adopters: Overall collection time		
high_subsidy							-410.843	-551.991	-495.263
							(0.099)*	(0.002)***	(0.004)***
medium_subsidy				-103.280	-491.430	-372.431			
				(0.807)	(0.216)	(0.303)			
no_subsidy	-595.416	-671.164	-826.766						
	(0.018)**	(0.030)**	(0.001)***						
c_dist_route_princ		-1.196	-3.094		-19.932	-19.127		4.298	5.318
		(0.854)	(0.619)		(0.225)	(0.137)		(0.343)	(0.243)
c_inst_known		686.512	1,754.924		61.073	84.125		1,078.307	849.793
		(0.002)***	(0.001)***		(0.942)	(0.910)		(0.016)**	(0.069)*
c_publictransport_good		62.457	274.612		1,379.540	1,116.815		-216.242	-40.233
		(0.812)	(0.245)		(0.098)*	(0.127)		(0.300)	(0.848)
c_mobilephonenetwork_good		7.807	180.705		243.534	408.703		-0.381	85.436
		(0.976)	(0.305)		(0.515)	(0.312)		(0.998)	(0.668)
c_admin_office		-434.159	-358.617		-27.925	165.157		-47.400	66.439
		(0.099)*	(0.185)		(0.954)	(0.704)		(0.854)	(0.791)
c_school		-27.654	-243.467		229.874	116.728		-443.360	-540.501
		(0.923)	(0.320)		(0.640)	(0.811)		(0.034)**	(0.009)***
c_health		928.462	622.072		-427.225	-568.242		1,166.463	1,063.609
		(0.014)**	(0.028)**		(0.406)	(0.246)		(0.007)***	(0.017)**
c_grid_el		-292.597	-108.019		-1,486.176	-939.671		80.586	50.214
		(0.266)	(0.669)		(0.100)	(0.211)		(0.651)	(0.780)
hh_size			115.395			65.587			110.192
			(0.009)***			(0.315)			(0.002)***
chef_literate			60.256			-110.261			-118.081
			(0.726)			(0.675)			(0.393)
chef_age			9.167			0.176			-6.506
			(0.152)			(0.979)			(0.166)
walls			24.524			-321.797			-142.334
			(0.900)			(0.212)			(0.477)
soil			-625.312			-1,006.718			-422.261
			(0.040)**			(0.009)***			(0.020)**
goat_sheep			137.073			712.607			75.123
			(0.484)			(0.007)***			(0.557)
pig			57.322			338.734			77.416
			(0.721)			(0.109)			(0.601)
cow			182.303			18.304			202.249
			(0.359)			(0.929)			(0.272)
transport			-595.264			398.666			-490.049
			(0.005)***			(0.423)			(0.011)**
Constant	1,250.866	1,433.593	215.057	1,426.502	1,881.547	1,207.863	1,485.471	1,396.619	1,135.962
	(0.000)***	(0.000)***	(0.541)	(0.000)***	(0.000)***	(0.039)**	(0.000)***	(0.000)***	(0.002)***
Observations	428	428	428	457	457	457	578	578	578
Adjusted R-squared	0.061	0.114	0.216	-0.001	0.108	0.185	0.014	0.083	0.123

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 12: Impact by adopters and non-adopters: fuel collection time

VARIABLES	Non-Adopters: Overall collection time			Non-Adopters: Overall collection time			Non-Adopters: Overall collection time		
high_subsidy							-57.968	-93.715	-80.924
							(0.770)	(0.643)	(0.660)
medium_subsidy				-15.864	-142.950	-84.080			
				(0.938)	(0.475)	(0.661)			
no_subsidy	-3.133	-80.141	-42.063						
	(0.986)	(0.653)	(0.803)						
c_dist_route_princ		16.065	12.327		1.201	-1.424		5.331	2.627
		(0.001)***	(0.009)***		(0.876)	(0.856)		(0.396)	(0.665)
c_inst_known		-292.975	-291.802		-92.176	-31.000		-214.504	-323.369
		(0.514)	(0.531)		(0.819)	(0.942)		(0.325)	(0.135)
c_publictransport_good		436.373	407.554		422.248	346.842		301.688	378.595
		(0.044)**	(0.058)*		(0.107)	(0.182)		(0.187)	(0.105)
c_mobilephonenetwork_good		-119.502	-5.664		-124.539	-0.906		60.643	99.830
		(0.497)	(0.972)		(0.526)	(0.996)		(0.765)	(0.595)
c_admin_office		-154.889	-74.679		-507.406	-444.553		-198.465	-198.639
		(0.538)	(0.762)		(0.051)*	(0.066)*		(0.441)	(0.388)
c_school		-174.915	-303.802		265.060	159.623		-232.094	-354.609
		(0.565)	(0.346)		(0.418)	(0.613)		(0.300)	(0.157)
c_health		441.942	375.151		323.803	199.169		311.478	285.879
		(0.048)**	(0.060)*		(0.182)	(0.375)		(0.157)	(0.164)
c_grid_el		41.521	114.351		-293.705	-161.131		-105.692	-91.958
		(0.858)	(0.615)		(0.336)	(0.584)		(0.595)	(0.631)
hh_size			88.043			101.158			82.985
			(0.003)***			(0.000)***			(0.023)**
chef_literate			-243.092			-117.376			16.291
			(0.082)*			(0.387)			(0.908)
chef_age			-3.103			-5.818			-4.557
			(0.412)			(0.082)*			(0.242)
walls			-208.746			-281.802			-36.286
			(0.091)*			(0.055)*			(0.836)
soil			-691.109			-591.312			-644.498
			(0.000)***			(0.011)**			(0.000)***
goat_sheep			211.785			100.387			114.810
			(0.071)*			(0.373)			(0.347)
pig			198.401			48.041			339.982
			(0.204)			(0.767)			(0.124)
cow			100.911			-86.481			199.888
			(0.452)			(0.527)			(0.155)
transport			-449.274			-429.398			-686.299
			(0.021)**			(0.014)**			(0.000)***
Constant	1,445.490	1,117.550	1,035.583	1,430.623	1,551.004	1,594.152	1,444.054	1,333.935	1,140.228
	(0.000)***	(0.000)***	(0.003)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.000)***	(0.003)***
Observations	810	810	810	789	789	789	679	679	679
Adjusted R-squared	-0.001	0.035	0.088	-0.001	0.019	0.061	-0.001	0.009	0.065

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Details on Figure 12: Impact by adopters and non-adopters: fuel collection time

VARIABLES	Adopters: Collection time per unit of firewood			Adopters: Collection time per unit of firewood			Adopters: Collection time per unit of firewood		
high_subsidy							0.010	0.011	0.008
							(0.161)	(0.218)	(0.258)
medium_subsidy				0.001	0.002	0.003			
				(0.840)	(0.753)	(0.494)			
no_subsidy	-0.002	-0.001	0.000						
	(0.442)	(0.683)	(0.968)						
c_dist_route_princ		-0.000	-0.000		-0.000	-0.000		-0.000	-0.000
		(0.020)**	(0.034)**		(0.136)	(0.098)*		(0.367)	(0.515)
c_inst_known		0.002	0.005		0.010	0.006		0.002	0.005
		(0.509)	(0.421)		(0.551)	(0.629)		(0.911)	(0.716)
c_publictransport_good		-0.005	-0.006		0.003	-0.003		-0.000	0.001
		(0.263)	(0.283)		(0.828)	(0.826)		(0.972)	(0.838)
c_mobilephonenetwork_good		-0.005	-0.003		-0.004	0.002		0.003	0.007
		(0.186)	(0.311)		(0.604)	(0.784)		(0.682)	(0.492)
c_admin_office		0.001	0.002		0.012	0.017		0.006	0.004
		(0.879)	(0.616)		(0.335)	(0.189)		(0.555)	(0.672)
c_school		-0.002	-0.004		-0.008	-0.007		-0.013	-0.018
		(0.457)	(0.229)		(0.408)	(0.275)		(0.078)*	(0.050)**
c_health		0.004	0.004		-0.004	-0.006		0.017	0.010
		(0.272)	(0.170)		(0.620)	(0.480)		(0.090)*	(0.322)
c_grid_el		-0.001	0.002		-0.005	0.006		-0.004	-0.000
		(0.764)	(0.749)		(0.747)	(0.685)		(0.476)	(0.951)
hh_size			0.001			0.000			0.002
			(0.398)			(0.886)			(0.038)**
chef_literate			-0.005			-0.005			-0.008
			(0.145)			(0.406)			(0.101)
chef_age			-0.000			-0.000			0.000
			(0.088)*			(0.371)			(0.474)
walls			-0.003			-0.007			-0.006
			(0.195)			(0.180)			(0.351)
soil			-0.003			-0.015			-0.009
			(0.554)			(0.086)*			(0.041)**
goat_sheep			0.005			0.018			0.008
			(0.258)			(0.107)			(0.355)
pig			0.002			0.017			-0.003
			(0.792)			(0.273)			(0.684)
cow			0.003			-0.006			-0.012
			(0.330)			(0.275)			(0.082)*
transport			-0.004			0.009			-0.008
			(0.099)*			(0.127)			(0.015)**
Constant	0.011	0.019	0.027	0.015	0.023	0.018	0.013	0.017	0.005
	(0.000)***	(0.000)***	(0.004)***	(0.002)***	(0.006)***	(0.049)**	(0.000)***	(0.008)***	(0.719)
Observations	336	336	336	358	358	358	440	440	440
Adjusted R-squared	-0.002	-0.014	-0.020	-0.003	-0.006	0.022	0.006	0.008	0.024

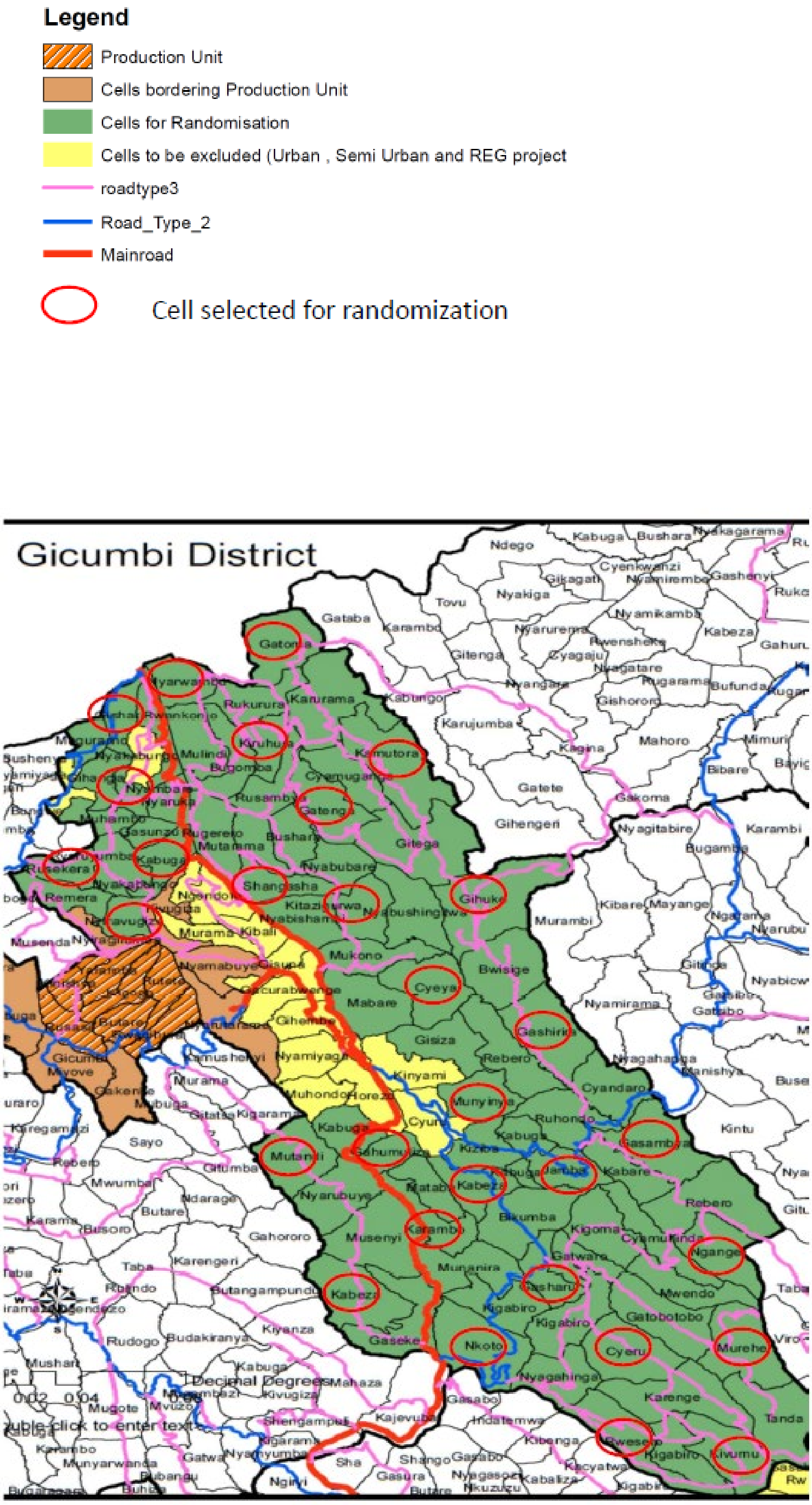
Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

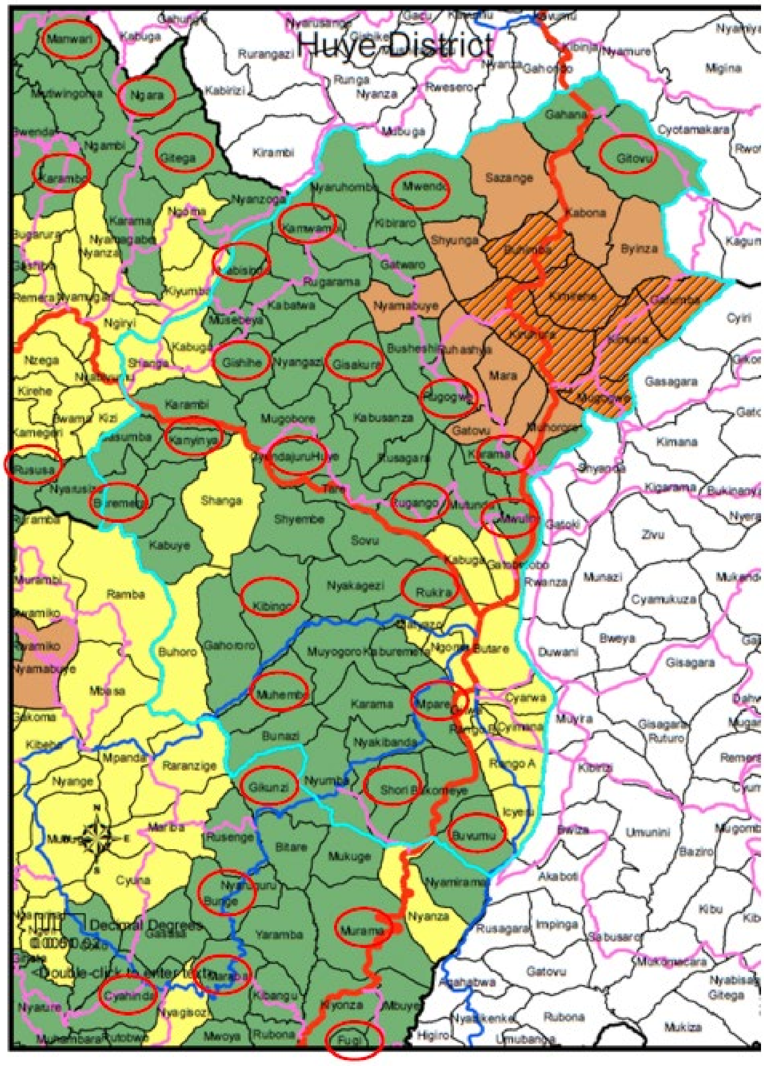
Details on Figure 12: Impact by adopters and non-adopters: fuel collection time

VARIABLES	Non-Adopters: Collection time per unit of firewood			Non-Adopters: Collection time per unit of firewood			Non-Adopters: Collection time per unit of firewood		
high_subsidy							0.004	0.008	0.008
							(0.559)	(0.208)	(0.228)
medium_subsidy				0.000	0.001	0.001			
				(0.954)	(0.879)	(0.736)			
no_subsidy	-0.004	0.001	0.002						
	(0.476)	(0.803)	(0.636)						
c_dist_route_princ		-0.000	-0.000		-0.000	-0.000		-0.000	-0.000
		(0.280)	(0.247)		(0.142)	(0.059)*		(0.430)	(0.455)
c_inst_known		0.011	0.009		0.006	0.008		-0.008	-0.012
		(0.025)**	(0.070)*		(0.557)	(0.322)		(0.401)	(0.223)
c_publictransport_good		-0.006	-0.008		-0.002	-0.006		0.006	0.005
		(0.505)	(0.432)		(0.789)	(0.428)		(0.473)	(0.548)
c_mobilephonenetwork_good		-0.010	-0.007		-0.007	-0.003		-0.002	-0.001
		(0.099)*	(0.143)		(0.202)	(0.395)		(0.769)	(0.787)
c_admin_office		0.017	0.019		0.003	0.006		0.011	0.011
		(0.278)	(0.223)		(0.756)	(0.513)		(0.488)	(0.445)
c_school		-0.002	-0.006		-0.002	-0.004		-0.013	-0.015
		(0.813)	(0.401)		(0.764)	(0.493)		(0.126)	(0.093)*
c_health		-0.001	0.001		0.002	0.002		-0.001	0.001
		(0.906)	(0.877)		(0.694)	(0.677)		(0.867)	(0.877)
c_grid_el		0.010	0.009		-0.000	0.003		-0.005	-0.004
		(0.249)	(0.209)		(0.969)	(0.691)		(0.507)	(0.622)
hh_size			0.001			0.001			0.001
			(0.166)			(0.100)*			(0.502)
chef_literate			-0.007			-0.003			0.000
			(0.205)			(0.379)			(0.990)
chef_age			-0.000			-0.000			-0.000
			(0.060)*			(0.217)			(0.689)
walls			-0.006			-0.010			-0.004
			(0.048)**			(0.013)**			(0.410)
soil			-0.010			-0.008			-0.007
			(0.014)**			(0.008)***			(0.108)
goat_sheep			0.007			0.006			0.008
			(0.298)			(0.250)			(0.274)
pig			0.013			0.011			0.013
			(0.381)			(0.348)			(0.292)
cow			-0.004			-0.009			-0.009
			(0.079)*			(0.053)*			(0.127)
transport			-0.004			-0.004			0.000
			(0.178)			(0.114)			(0.992)
Constant	0.016	0.019	0.024	0.015	0.023	0.026	0.015	0.019	0.020
	(0.001)***	(0.005)***	(0.000)***	(0.000)***	(0.001)***	(0.001)***	(0.000)***	(0.006)***	(0.095)*
Observations	623	623	623	641	641	641	534	534	534
Adjusted R-squared	-0.001	0.012	0.027	-0.002	-0.004	0.018	-0.001	-0.001	0.005

Notes: Robust standard errors clustered at village level in parentheses. c_dist_route_princ: distance to principal route in km; c_inst_known: = 1 if installer participated in earlier stove campaigns; c_publictransport_good: access to public transport easy or very easy; c_mobilephonenetwork_good: mobile phone network is good; c_admin_office: cell bureau in community; c_school: any type of school in community; c_health: any type of health infrastructure in community; c_grid: access to national electricity grid in community; chef_literate:=1 if hoh visited at least alphabetisation courses; chef_age: hoh's age; hh_size: number of household members including children; walls: wall material is better than wood or clay/mud; soil: soil material is better than earth; cow: = 1 if household owns cows; goat_sheep: = 1 if household owns goats and/or sheep; pig: = 1 if household owns pigs; transport: = 1 if household owns means of transport;

Appendix 4 - Maps for establishing list of non-adjacent cells.




Huye District
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Ngara
Gitega
Karambi
Kabuga
Kabirizi
Rurangazi
Kirambi
Runga
Nyanza
Rwesero
Mubuga
Migina
Cyotamakara
Gahana
Gitovu
Sazange
Kabona
Byinza
Mwendo
Nyaruhombo
Kamwambi
Kibiraro
Shyunga
Gatwaro
Rugarama
Nyamabuye
Nyanzoga
Kabatwa
Musebeya
Gishihe
Nyangazi
Gisakura
Busheshi
Ruhashya
Mara
Gasagara
Cyiri
Kimana
Kabusanza
Mugobore
Karambi
Kanyinya
Rususa
Kizi
Nzega
Kirehe
Ngiryi
Shanga
Rusagara
Gatovu
Karama
Shyanda
Rugango
Mutunda
Mwulire
Gatoki
Zivu
Shyembe
Sovu
Kabuye
Kabuga
Rwanza
Munazi
Cyamukuza
Nyakagezi
Rukira
Kibingo
Ramba
Buhoro
Gahororo
Muyogoro
Butare
Bweya
Duwani
Gisagara
Muhembe
Karama
Mpare
Cyarwa
Mbasa
Bunazi
Nyakibanda
Rango A
Kibirizi
Gikunzi
Nyumba
Shori
Icyeru
Buvumu
Bitare
Mukuge
Nyamirama
Rusenge
Umunini
Baziro
Akaboti
Cyuna
Mpanda
Raranzige
Nyange
Mariba
Bunge
Nyanza
Yaramba
Murama
Rusagara
Impinga
Sabusaro
Mukomacara
Kibu
Gatovu
Kibangu
Nyonza
Mbuye
Rubona
Mwoya
Fugi
Higiro
Umubano
Mukiza
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Cyahinda
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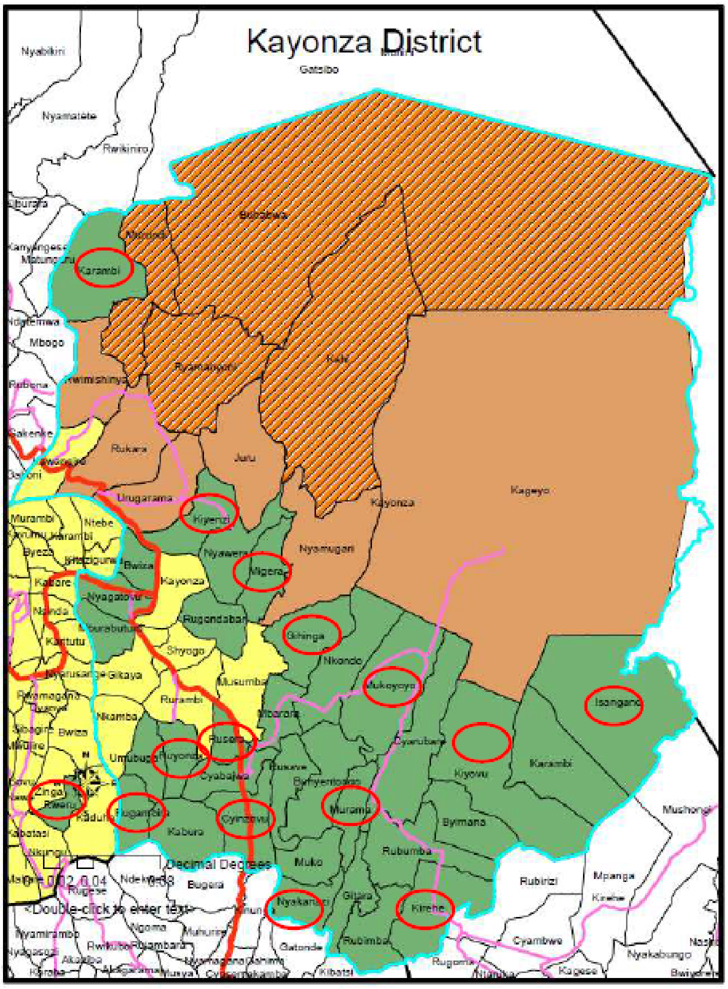
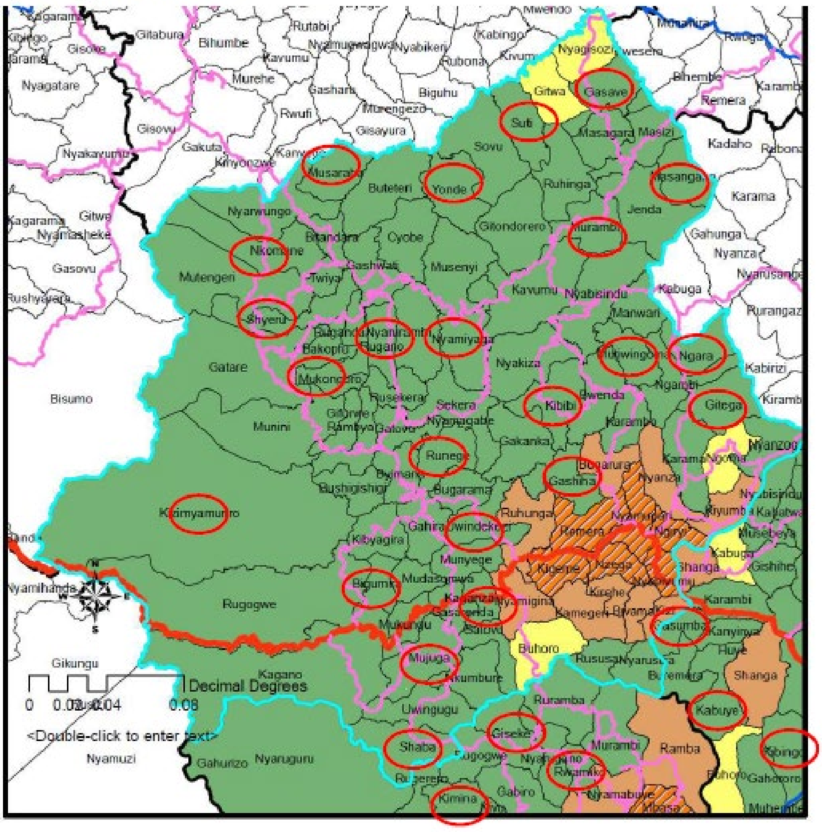
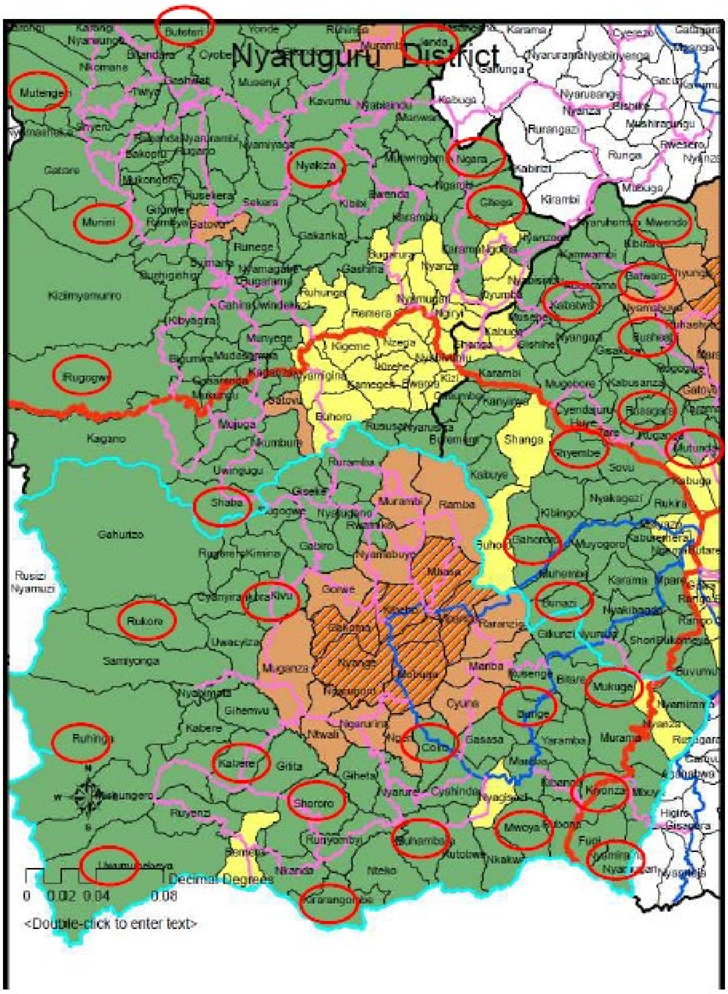

Kayonza District

Nyamagabe District




Nyaruguru District
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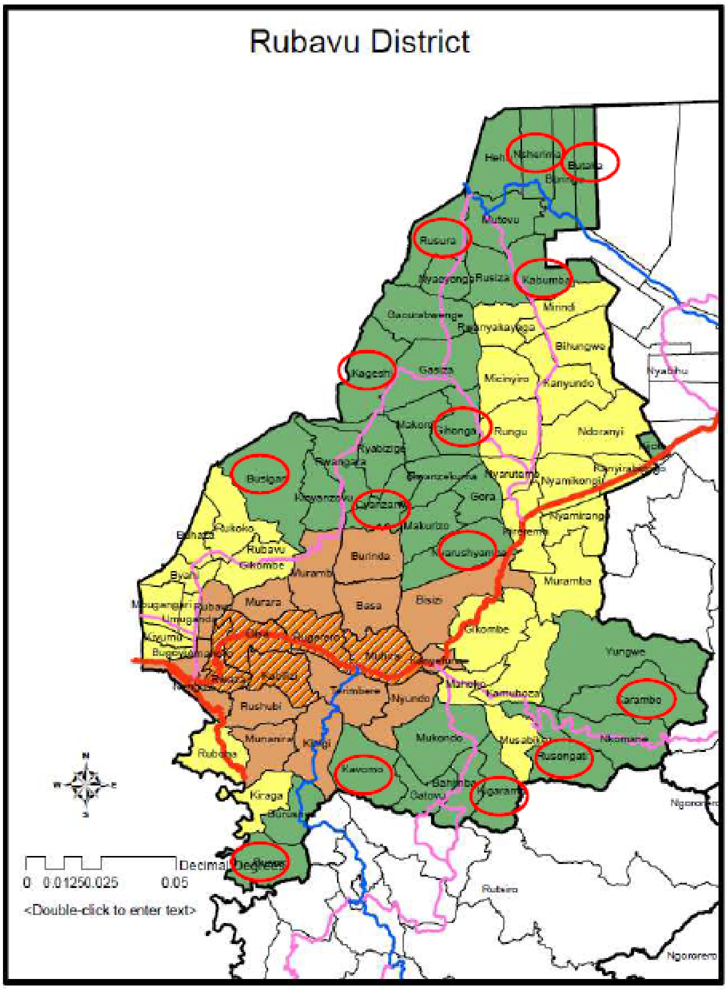
Rubavu District
Mutovu
Rusura
Rusiza
Kabumba
Mirindi
Gacurabwenge
Bihungwe
Kageshi
Gasiza
Micinyiro
Kanyundo
Nyabihu
Rungu
Ndoranyi
Mukore
Gihonga
Busigari
Rwangara
Ryabizige
Gora
Nyamikongi
Kayanzovu
Makurizo
Nyamirango
Rubavu
Gikombe
Burinda
Muramba
Murara
Basa
Bisizi
Yungwe
Rushubi
Nyundo
Kamuhoza
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Rusongati
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