Waste Not: Can Household Biogas Deliver Sustainable Development?

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Abstract

Household biogas systems are a renewable energy technology with the potential to provide sustainable development benefits by reducing pressure on forest stocks and by shifting household time allocation towards higher value activities or long-term investments in human capital. We estimate the environmental and socioeconomic impacts of biogas expansion in Nepal using an instrumental variables approach that exploits conditional variation in access to biogas installation companies. We confirm prior evidence that biogas use significantly reduces collected fuelwood, estimating changes of approximately 800-2000 kg per year per household. We find new evidence that biogas saves time in fuelwood collection (23-47%), and results in reallocation of time away from home production and wage labor towards agricultural labor and education. We find that biogas reduced forest cover loss in the Hill region and when combined with other forest protection policies. Together the results suggest that biogas can contribute modestly to sustainable development, particularly in combination with complimentary opportunities or policies.

Keywords: deforestation, double dividend, environment, renewable energy technology, sustainable development, time use

JEL codes: O13; O15; Q42; Q56; Q58

1. Introduction

Access to energy services such as electricity, natural gas, and other modern cooking fuels contributes to development by improving both living standards and productivity (World Bank 2006, Barnes et al. 2010). Indeed, electrification has been shown to increase hours devoted to work outside the home (Dinkelman 2011), to raise education, income, and formal employment levels (Lipscomb et al. 2013), and to enhance agricultural productivity through irrigation and mechanization (Assunção et al. 2015). However, the relationship between increased access to energy and local environmental quality remains understudied. This relationship is important because investments in energy choices today may positively or negatively affect the welfare of future generations and thus sustainability (Solow, 1993; Pezzey and Toman 2003). There is evidence that many prior pro-poor developments have actually increased resource use, by encouraging consumption of goods that are forest-intensive (Baland et al. 2010), energy-intensive (Wolfram et al. 2012) or land-intensive (Alix-Garcia et al. 2013). Similarly, with increased wealth, households may increase fuel consumption and could switch to more polluting fuels, rather than moving up a clean "energy ladder" (Arnold et al. 2006, Hanna and Oliva 2015).

In this paper, we evaluate household use of biogas in Nepal with the goal of understanding its socioeconomic and environmental impacts. Biogas systems produce clean cooking fuel by capturing methane and other combustible gases emitted during the breakdown of animal manure and human waste (Bond and Templeton 2011, Surendra et al. 2014, Christiaensen and Heltberg 2014). Their potential environmental benefits include reduced greenhouse gas emissions due to displaced fossil fuel use and direct capture of methane, and reduced deforestation or forest degradation in areas where wood is a primary cooking fuel.[1] Biogas may thus provide a greener energy option, particularly for the 3 billion people who still rely on traditional biomass fuels such as wood and dung (United Nations, 2016). Recent analyses in Nepal (Somanathan and Bluffstone 2015) and China (Christiaensen and Heltberg 2014) suggest that households with biogas use less fuelwood than non-biogas households, by magnitudes of 46% and 47%, respectively. Other studies also find biogas associated with less fuelwood use (Singh and Maharjan, 2003 ~60% in Nepal; Gosens et al. 2013 ~30-60% in China, depending on the province; Garfi et al. 2012 ~ 50-60% in Peru). A recent study in India also finds that forests close to villages with biogas interventions had greater biomass than matched controls (Agarwala et al. 2017).

Biogas also has potential socioeconomic benefits which include time and money saved due to reduced use of biomass fuels and health benefits from cleaner-burning fuel. Surveys from Nepal suggest that households with biogas believe they spend less time and money on fuel, spend more time on schoolwork and other productive activities, have better health and have more empowered women (SETM 2014). Christiaensen and Heltberg (2014) found that 98% of households reported time saved in cooking and found fuel-collection time-savings of 24 days per year for women, 10 days for men, and 4 days for children.[2] In general, time saving technologies have the potential to increase economic development by shifting time from home production to income generating

[1] Dhingra et al (2011) find that biogas households have 23-55% lower global warming contribution than non-biogas households, taking into account the 3% of biogas systems that had methane leaks. Rajendran et al. (2012) summarize the literature on biogas and greenhouse gas emissions.

[2] There is also evidence of household health benefits from studies in Nepal (Pant, 2008 and 2011) and China (Christiaensen and Heltberg, 2014) comparing households with and without biogas.

activities. Time-saving technologies have increased labor force participation in both developed (Greenwood et al. 2016, Cavalcanti and Tavares 2008, Coen-Pirani et al. 2010) and developing countries (Dinkelman 2011, Meeks 2017), and have also increased time allocated to leisure, which may be welfare-improving (Devoto et al. 2012). This paper investigates whether the biogas technology reduces the time-intensity of home production and, if so, to what activities do households reallocate these time savings.

With these expected dual benefits for economic development and environmental quality, biogas is a technology with potential to contribute to sustainable development. Biogas promises to reduce pressure on forest stocks, to reduce greenhouse gas emissions, and to free-up additional time for households to use productively. Each of these changes may improve welfare both for current and future generations: less pressure on forest resources in the present could allow more long-term forest regeneration and protect biodiversity, fewer greenhouse gases would mean less future warming, and additional household time could be used for investments in education or improvements in land productivity. Yet achieving a "double dividend" for both forest cover and livelihood improvement with a single policy or technology is not easy to do in practice, as suggested by several recent analyses (e.g. Alix-Garcia, Sims and Yanez-Pagans 2015, Jeuland and Pattanayak 2012, Kohlin et al. 2015).[3] Prior research on energy technologies, such as improved cookstoves, finds lower than expected benefits due to improper use, maintenance problems, and incompatibility with traditional food-preparation practices (e.g. Hanna et al. 2014, Levine et al 2012, Miller and Mobarak 2014). Biogas could also suffer from these issues.

[3] In addition, Kohlin et al. (2015) argue that there is a large "know-do gap" between research on sustainable development technologies and what is actually implemented globally.

Additionally, biogas requires time to collect the dung and water necessary for the system, potentially mitigating impacts on time allocation.

Similarly, biogas may not necessarily reduce resource use overall. In some cases, improved cooking technologies and access to modern fuels were shown to have little or no effect on the amount of fuelwood used (Hiemstra-van der Horst and Hovorka, 2008; Nepal, Nepal and Grimsrud, 2010).[4] And, even if individual households do reduce their fuelwood consumption following biogas adoption, these impacts may not accrue locally or they may be smaller than expected. For example, in the presence of well-connected markets for firewood, families may sell surplus wood or may purchase less from other locations, making local forest cover impact difficult to detect.[5] Furthermore, if biogas use increases time available for agriculture, deforestation could actually increase due to additional land clearing.

In short, further empirical analysis is needed to better understand the extent to which socioeconomic and environmental impacts follow biogas construction. To date, the empirical literature on the impacts of biogas is based either on comparisons of households with and without biogas or on small samples that are likely non-representative. Estimating the causal impacts of biogas installation is difficult due to the endogeneity of adoption: households that adopt biogas systems are likely to differ systematically from non-adopters. In addition, biogas

[4] Not finding measurable impacts could also be due to missing complimentary institutions; for example, Meeks (2018) has found that formalizing property rights played a role in increasing household access to energy (and other services) in rural Peru.

[5] Work by Chakravorty et al. (2015) suggests an important role of fuelwood markets on collection times in neighboring India.

may be promoted as part of broader forestry programs or development programs that could directly affect environmental and social outcomes. Thus, analyses relying on comparisons between all households with and without biogas may produce biased estimates, the direction of which is unclear.[6] There are various approaches to minimize such biases. For example, recent papers by Somanathan and Bluffstone (2015) and Christiaensen and Heltberg (2014) use local fixed effects along with a detailed set of controls, thereby attempting to account for selection on observables. To avoid possible bias from omitted variables, self-selection, or simultaneity, we use an instrumental variables approach that exploits plausibly exogenous variation in distance to biogas installation companies to estimate biogas impacts.

We seek to improve upon prior literature by providing the first instrumental variables-based evidence on the impacts of biogas and by investigating both socio-economic and environmental impacts at a national scale. We combine census micro-data from 2011 and 2001, nationally representative household survey data collected between 2003 and 2010, remote sensing data on changes in forest cover from 2000-2012 (Hansen et al. 2013, ICIMOD), and administrative data on the expansion of biogas across the country over time. Following Baland et al.'s study of firewood use in Nepal (2010), we estimate different impacts for the Terai and Hill regions, which are substantially different in terms of land ownership, education levels, geographic characteristics, and climate.

[6] For example, if more educated or entrepreneurial households are also more likely to install biogas and use it optimally, then analyses comparing households with and without biogas may result in overestimates of impacts. If, on the other hand, households that install biogas are more entrenched in agricultural production (e.g. have more livestock) or less entrepreneurial, the estimated impact of biogas may be downward biased.

Informed by conversations with biogas experts in Nepal, our instrumental variables strategy employs spatial variation in new biogas branch locations that result from government programs and happenstance, conditional on controls for market access, transportation accessibility, baseline branch locations, and terrain. Government promotional programs differentially encouraged biogas adoption in particular districts between 2001 and 2011 by providing a combination of subsidies and requirements for biogas installation companies to expand their operations. Plausibly causal identification relies on two important assumptions. First, households with greater access to installation opportunities—i.e. those located closer to a biogas company branch—are more likely to adopt biogas than households with less access. Second, biogas company branch locations, conditional on included controls for other potentially endogenous factors, are driven by factors uncorrelated with household demand for biogas, other government programs, or labor opportunities. This provides a source of conditional variation in biogas adoption that is exogenous to other household and district characteristics. Maps of the identifying variation and placebo tests of the instrumental variable (on other key energy sources, such as LPG and electricity) provide supporting evidence that the exclusion restriction is likely to hold.

Results indicate that biogas reduces traditional fuel use, including both the amount of fuel collected and purchased, as well as the time spent in collection, across both Hill and Terai regions. In both regions, biogas decreases time spent in wage labor and increases time spent in educational studies for households in aggregate (all members above age 10). Within the Terai region, biogas leads to a substantial shift away from time spent in home production and towards time spent in agriculture, a change which may be explained by the complementary use of biogas fertilizer byproduct or because agriculture is the highest value alternate activity in the Terai. Within the Hill, biogas has small and not statistically significant impacts on home production, possibly because of the additional time needed to collect water for biogas systems. With respect to forest cover, we find that biogas significantly increased forest cover in the Hill region as well as when combined with other forest protection policies (protected areas and community forest user groups).

Overall, the results indicate that biogas has moderate impacts on time-allocation and resource use. These changes are potentially welfare-improving, assuming they represent shifts towards higher value activities. However, this is not a given, and suggests that long-term, sustainable improvements in household welfare from biogas installations depend on the presence of complementary conditions such as greater agricultural productivity or prices, higher wage opportunities for better-educated adults, and mechanisms for long-term environmental protection. This highlights the importance of context-specific, integrated approaches to promoting renewable energy technologies.

2. Background

2.1 Nepal Context

Due to the number of energy-poor households and the recent promotion of renewable energy technologies within the country, Nepal provides an ideal context in which to study biogas's economic and environmental impacts. One-third of the country's households lack access to electricity and 75% rely on wood or dung for cooking (Nepal Census 2011). One of Asia's least developed countries, much of Nepal is remote and characterized by high poverty rates and a lack of economic opportunity.[7] In addition, natural resources have increasingly been strained in Nepal, with forest cover falling from 38.1% in 1978/79 to 29% in 2001 (CBS 2014).

Nepal has developed a portfolio of renewable energy technologies, such as biogas, wind, solar, and micro-hydro, to provide energy to its underserved and remote areas. Although biogas was promoted for more than 20 years in Nepal, the largest installation increase occurred in the past decade. As of 2015, more than 300,000 household biogas systems were installed (~4% of households; data from AEPC, Barnhart 2012, Bajgain and Shakya 2005). Along with international partners, the government of Nepal heavily invested in biogas through large subsidies, product quality oversight, and credit facilitation for biogas construction. A key partner in developing and maintaining this portfolio is the Alternative Energy Promotion Centre (AEPC),[8] a government entity within the Ministry of Science, Technology, and Environment. AEPC tracks household biogas installations, making this empirical analysis feasible. Figure 1 maps the percent of households in each Village Development Committee (VDC) with installed biogas in both 2001 and 2011.[9]

Nepal is comprised of three ecological belts, which include the Mountains, Hill, and Terai. These belts differ in climate, terrain, culture, and access to markets and infrastructure. For example, although wood is the primary traditional fuel source throughout Nepal, many areas in the Terai

[7] 25.2% of the population lives below the national poverty line (World Bank, 2016).

[8] AEPC works together with the Biogas Promotion Program (BSP) to support biogas expansion.

[9] VDCs should be thought of as sub-districts – there are 3973 VDCs within the 75 districts of Nepal.

use dried cow dung. As biogas requires minimum temperatures to operate, the technology is generally inappropriate for the Mountain region. [10]

2.2 What is Biogas?

Home biogas systems use anaerobic digestion to convert human and animal waste into a clean, odorless gas that can be used for cooking, heating, and lighting, although it is mainly used for cooking in Nepal (Winrock International, 2003). In addition to the production of the gas itself, biogas systems produce fertilizer (bioslurry) as a byproduct, which lab studies have shown to be just as, if not more, effective than the traditional dung fertilizer (Karki, 2006).[11] Finally, although large livestock (cows, buffalo, oxen) are required to adequately fuel the digester, biogas systems can also be connected to a latrine and used as a septic tank. Figures 2a and 2b provide a stylized diagram and a photo of a typical biogas system, which are 6 cubic meters on average and constructed mostly underground on the household's property. Each day, the digester requires dung and water to be added, a chore typically performed by females. Biogas systems can connect via pipe to kitchen stoves, enabling cooking with ease within the kitchen.

Biogas systems are a costly investment for the household, averaging 475 USD[12] (or approximately 47,000 NRs) but ranging from 250-700 USD (approximately 25,000 to 70,000

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[10] Most of the mountain area is excluded because it is too cold for biogas. We included 190 mountain VDCs that had biogas systems installed by 2011. We include a control for mountain region but group these observations with the Hill for regional comparisons. We exclude the Kathmandu District from analysis because most of the households are not suitable for biogas and there are no good counterfactuals given its unique status as the capital and major international hub of the country. Robustness checks including this district yield similar results.

[11] Indeed, some households in Nepal cite the bio-slurry as the main reason they chose to invest in a biogas system.

[12] Calculations are based on the 2013 exchange rate of 1 USD = 98.98 NPR.

NR) (SETM, 2013) even after subsidies are included.[13] The same study found that 80% of biogas users surveyed had a monthly income of 200 USD or less. The total installation process, which must be completed during the dry season (October-May), takes approximately one month (Karki, Shrestha, and Bajgain 2005). Biogas systems are intended to function for over 20 years and, as part of the accreditation and subsidy programs, the biogas companies provide 3 years of maintenance and service.

3. Data and Variable Construction

Our analysis combines data from multiple sources: micro-data from the country's census in 2001 and 2011, the 2003 and 2010 Nepal Living Standards Survey (NLSS), the 2008 Nepal Labor Force Survey (NLFS), official AEPC records and documents, and interpreted satellite data on forest cover from Hansen et al. (2013) and the International Center for Integrated Mountain Development (ICIMOD). Census, NLSS, and NLFS data are at the household level, while biogas installation data and forest cover data are calculated at the VDC level.

3.1 Household data

Census

The 2001 and 2011 census micro-data are from the Central Bureau of Statistics in Nepal and contain information on demographics, assets, basic household characteristics, education, and employment for 841,567 (15.5%) and 520,624 (12.2%) households, respectively.[14] We use the

[13] Costs vary depending both on location and whether the household must purchase the required construction materials (brick, stone, cement, etc.) and unskilled labor or whether they can obtain them in kind.
[14] Due to political turmoil, 2001 census enumeration was disturbed in 83 VDCs (across 12 districts); these VDCs are thus excluded.

2011 micro-data for our economic outcome variables as well as household and VDC level covariates. We used the 2001 data to construct baseline covariates.[15]

The census data reports limited information on the economic and non-economic activities of each family member over age 10. Our primary labor outcome variable is the percent of months devoted to each of five activities: home production (combining household chores and extended economic work), agriculture, wage or salaried work, small business activities, and studies. Home production includes cooking, cleaning, and caring for household members, as well as any production of goods or services for home consumption including fuel and water collection, preparation of foodstuff and livestock feed, etc. Because males and females are often engaged in different activities and biogas is expected to primarily affect the time allocation of females, we present results for household labor allocation by gender of the household member.

Household-level covariates that likely influence biogas adoption or labor decisions are also created from the census micro-data. Household covariates include number of household members under 10, aged 10-17, and older than 18; head of household education; ownership of home, TV, toilet, radio, and tap water; electricity as main lighting fuel; and ethnicity. Covariates were also aggregated to VDC averages (for continuous variables) or proportions (for categorical variables) for VDC-level analysis. These include population, the average number of livestock owned by VDC households, and the respective percentages of households owning land and livestock, with female members owning land, engaged in agriculture, or engaged in any non-

[15] The 2001 time allocation information was collected differently and so we could not construct the same outcome variables for this year and cannot use the data as a panel at the VDC level.

agricultural business. Household ownership of land and livestock variables were only collected in 2001.

NLSS and NLFS

The Nepal Living Standards Survey is a nationally representative household survey also managed by the Central Bureau of Statistics. We use the most recent two rounds: NLSS-II and NLSS-III, which were conducted in 2003/04 and 2010/11 and sample 3912 and 5988 households, respectively. We also use the Nepal Labor Force Survey 2008 (NLFS), which is managed by CBS and interviews 15,976 households.

Both NLSS survey rounds collect detailed information on household fuelwood collection and expenditures. NLSS-III and the NLFS include detailed information on time allocation for home production in the past week for household members older than 5 years of age. All surveys include the data necessary to create the previously described household-level covariates, as well as the amount of land owned by the households. In addition, the NLSS survey rounds report the number of livestock owned by the household, the location of firewood collection, and per capita consumption.

Biogas installations and primary cooking fuel

We collected programmatic data from AEPC on the history of subsidized biogas installations in Nepal (the vast majority of household systems) and matched these to VDC. These system-level data provide the exact date of system completion, the location (VDC)[16], basic system

[16] 5,000 of 293,000 installations (1.7%) up through 2011 could not be matched to census VDC codes

characteristics, and the company branch that sold the system and oversaw construction. We used these data for VDC-level analysis as well as identifying when biogas company branches were in operation in each VDC.

Information on biogas use is also available in survey data; both the census and the NLSS/NLFS report primary cooking fuel. The NLSS also reports whether the household produces any biogas for home consumption. In that dataset, we consider households as biogas users if they either report biogas as their main cooking fuel, or report producing any biogas. Because we want to compare households with biogas to those using traditional fuels, we limit our analysis to households who use dung, wood, or biogas as their main cooking fuel.[17]

3.2 Forest Cover

To study changes in forest cover at the VDC level, we use recent global data available from Hansen et al. (2013), combined with data from researchers based at Nepal's International Center for Integrated Mountain Development (ICIMOD; Uddin et al. 2015). These two sources are the only measures of comprehensive data on forest cover in the most recent decade that cover all of Nepal.[18] Both are based on interpretation of images from the US Landsat satellites (30 m resolution), but using different classification and change detection algorithms. The Hansen et al. data spans 2000-2012 and the ICIMOD data 2000-2010. All classified land cover products include error due to the difficulty in interpreting land cover where there are shadows from clouds

[17] We exclude households using electricity, LPG, kerosene, or "other" main cooking fuels.

[18] Similar use of the Hansen et al. (2013) dataset to evaluate conservation initiatives is growing, e.g. Brandt et al. (2016), Wiesse and Naughton-Treves (2016), Sims and Alix-Garcia (2017) and Alix-Garcia, Sims and Yanez-Pagans (2015).

or topography and because land classes give different reflectance signals depending on availability of rainfall and timing of vegetation growth in a given year. Given errors in both data sources, we use the averaged value across the two sources. We calculate net forest cover change both as a percent of total area in the VDC and as a percent of initial VDC forest cover in 2000. Fuelwood collection may affect mainly forest quality, yet we note that our forest cover measures span 10+ years, a period over which repeated pressure from firewood collection could affect forest regeneration or susceptibility to disease, pests or fire, and thus affect overall forest cover.

We also incorporate data on the two major types of official forest protection policies in Nepal: community forest management and government protected areas. (e.g. National Parks and Conservation Areas). Community forest user groups (CFUGs) are de-centralized institutions with local control over the use of forested areas, including regulating access to firewood, timber, and fodder resources (Ojha, Persha and Chhatre 2009, Bluffstone et al. 2014, Paudel 2016). There are over 15,000 CFUGs involving 1.8 million households in the management of 1.35 million hectares of forest and shrub-land (Sharma et al, 2015). Data on CFUG locations comes from the Nepali Department of Forests database on community forest user groups.[19] Information on protected areas is from the IUCN-UNEP WCMC World Database of Protected Areas (accessed in 2015), and the underlying source is from Nepal's Dept. of National Parks and Wildlife Conservation.[20] Prior work on these two types of forest protection find generally positive impacts for forests and livelihoods. Previous studies find that CFUGs are associated

[19] We gratefully thank Johan Oldekop for sharing this data as well as the forest cover data from Hansen et al. at the VDC level. The CFUG data is described in more detail in Oldekop et al. 2017b.

[20] This includes land under strict protection, conservation areas, and buffer zones and covers approximately 20% of Nepal's land area.

with greater forest carbon stocks (Bluffstone et al. 2015) and other improvements in forest health (Tachibana and Adhikari 2009). CFUGs have been found to increase food consumption for nearby households (Paudel, 2016) while protected areas have been found to reduce consumption of forest-goods without increasing reliance on market purchases (Howlander and Ando, 2016) and to increase local welfare when combined with ecotourism (Yergeau, Boccanfuso, and Goyette 2017). Oldekop et al. (2017b) finds positive impacts of community forests for forest cover and livelihoods, but smaller impacts where baseline poverty is high.

We limit the analysis of forest cover data to VDCs with at least some forest cover at the start of the period, defined as having 10 hectares or more of forest cover and at least 1% of area forested in 2000.[21] This reduces measurement error due to potentially large percentage changes where there is very little forest cover at baseline. Because we are interested in the potential for biogas to achieve a double-dividend, we also limit the census analysis to the same set of VDCs, although using the full household sample yields similar results (available upon request). We use all available NLSS households due to the survey's smaller sample size.

4. Empirical Strategy

4.1 Instrument: Access to Biogas Company Branches

Following an empirical strategy similar in spirit to that of Burgess and Pande's (2005) study of rural bank expansion in India, our empirical analysis exploits policy-generated differences in the locations of biogas company branches. Specifically, we instrument for biogas adoption at the household and VDC level with a measure of access to company branches, conditional on

[21] This is based on the Hansen measures and excludes about 20% of VDCs, mostly located in the Terai region.

controls for overall market access and other possible determinants of company location that could be correlated with household demand or other government policies.

First, it is necessary that access to a company branch be a determinant of biogas installations. This is true in Nepal because of the system of installations. A prominent feature of Nepal's biogas program is its partnership with the private sector. Although the government subsidizes and promotes biogas, system installations ultimately depend on household purchases through private companies, which operate via branches located throughout the country and serving nearby communities. To receive government subsidies, biogas operators must register and meet particular criteria. As of 2016, approximately 100 biogas companies were approved to receive subsidies. Trained technical experts from these biogas company branches transport and install biogas-specific materials (e.g.; gas valves, stoves, pipes, and fittings) to each biogas construction site, making the companies more likely to serve consumers that are closer to the branch.

To create a measure of access to biogas companies, we used programmatic data from AEPC on the history of subsidized biogas installations in Nepal. We used the AEPC biogas installation data to compile a historic list of all companies and their respective branches that installed subsidized biogas systems between 2001 and 2011. We then used several sources (Winrock International, 2003; AEPC Biogas User' Surveys (2001-2008); and AEPC internal documents) to match the branches to VDC addresses and those addresses to census VDC codes.[22] We used mapping software to calculate Euclidean distance from each VDC to the nearest VDC with a

[22] Of the 215,668 systems installed between 2001 and 2011, we matched the company branch to a location for all but 5,951 installations (~3%). The remaining 73 unmatched branches either existed very briefly and thus were never included on any official list, or were incorrectly coded in the administrative data.

biogas branch in each year. Our unconditional measure of access is the average distance from the VDC to the nearest VDC with a biogas branch for the years between 2002 and the year of the outcome data.

Second, instrument validity requires that the source of variation driving biogas adoption not be a direct determinant of the outcome variables. Clearly, biogas branches are not randomly distributed throughout the country. Their locations are likely correlated with other factors - such as overall market access, frequency of households with livestock, fuelwood availability and other government programs - all of which could influence household time use and forest cover outcomes. For this reason, our instrumental variables approach does not use all of the variation in branch location. Instead, we use the variation remaining after controlling for other potentially endogenous factors at the VDC and household level. These are described in detail in Table 1 and include distance to the nearest biogas branch at baseline (2001), distance to the nearest population centers, distance to Kathmandu, distance to the nearest road, VDC size, slope, elevation, precipitation and baseline population, household asset ownership, access to electrification, and household size.

We argue that the remaining variation is plausibly exogenous due to variation in government incentives to establish new branches, as well as happenstance in location. Although there is no direct way to test this assumption, we provide supporting maps and placebo tests for take-up of LPG fuel and electrification, alternative energy sources often correlated with greater wealth and market access.

The structure of government policies promoting biogas across Nepal during the 2000s provides a source of variation in otherwise unlikely areas. Although biogas expansion occurred through the private sector, AEPC was highly involved in the technology's expansion, providing large subsidies (up to 40% of cost) to pre-approved biogas companies, as well as quality enforcement for installations and maintenance. To expand biogas into underserved and remote areas, AEPC implemented policies in the early 2000's designed to encourage biogas company expansion into these areas. In 2006, AEPC introduced an additional subsidy for biogas systems constructed in an official set of "less penetrated districts (LPDs)" (Figure 3). For companies to maintain their pre-approved status, they were required to install systems and open company branches in LPDs.

Figure 4 displays the location of all branches operating in alternate years between 2001 and 2011 in relation to measures of market access. The figure shows that in 2001, branches tended to be located in population centers. However, between 2002 and 2011, access to biogas companies increased across the country, particularly in more remote areas. Over time, branch locations became less concentrated as companies responded to government policy and expanded into these new markets. The maps indicate that there is some apparent randomness in the locations of branches over time—e.g. branches pop up (and sometimes disappear) in places without obvious connectivity to markets or locational advantages. Most likely, this is due to imperfect information and experimentation on the part of biogas companies, and provides a further source of plausibly random variation in access during this period. These maps, however, do not show only our identifying variation. To better isolate the source of variation we utilize in our empirical strategy, Figure 5 plots the residuals from a regression of biogas branch distance on the other first stage variables; thus showing the residual variation in branch distance that predicts biogas and thus identifies our results.[23] The map in Figure 5 portrays high and low residuals distributed across the country, including in areas close to and far from urban areas and major roads. The heterogeneity portrayed in the map thus provides evidence in support of the conditional exogeneity assumption; placebo test results are also described below.

4.2 Household Analysis: Wood collection and time allocation

We first examine the impact of biogas on household firewood collection and time allocation. We apply the three-stage IV approach discussed in Wooldridge (2002) that takes into account the binary nature of our endogenous variable and provides valid standard errors for our estimates. In each stage, we use robust standard errors, clustered at the VDC level. We include interactions with Hill to allow the impacts of biogas to vary by region (as detailed earlier).

The first stage uses a logit regression, where $F(.)$ is the cumulative logistic distribution function, to predict the probability that household *i* in village *v* uses biogas as a function of our branch access instrument and sets of both household (X_{iv}) and VDC-level (V_v) time-consistent and aggregated baseline controls from 2001:

$$\Pr(BG_{iv} = 1) = \mathrm{F}(\vartheta + \sigma_1 BRANCH_v + \sigma_1 BRANCH_v x Hill_v + \Delta_1' X_{iv} + \Gamma_1' V_v) \qquad \textbf{(1)}$$

We then use predicted biogas and the interaction between predicted biogas and Hill as instruments in a standard two stage least squares estimation of the impact of biogas in both

[23] This is similar to the map illustrating the instrument in Madestam et al. 2013.

regions on household outcomes (equations 2-4). We include a dummy variable for dung use[24] and the same set of household and VDC controls. This means the omitted category is households who use wood, so the estimates should be interpreted as the impact of changing from wood to biogas.

$$BG_{iv} = \pi_1 + \theta_{11}\widehat{\Pr(BG)}_{iv} + \theta_{12}\widehat{\Pr(BG)}_{iv}\text{x}Hill_v + \Delta_1' X_{iv} + \Gamma_1' V_v + \omega_{1iv} \quad \textbf{(2)}$$

$$BG_{iv}\text{x}Hill_v = \pi_2 + \theta_{21}\widehat{\Pr(BG)}_{iv} + \theta_{22}\widehat{\Pr(BG)}_{iv}\text{x}Hill_v + \Delta_2' X_{iv} + \Gamma_2' V_v + \omega_{2iv} \quad \textbf{(3)}$$

$$Y_{iv} = \alpha + \beta_1 \widehat{BG}_{iv} + \beta_2 \widehat{BG}_{iv}\text{x}Hill_v + \Phi_1' Dung_{iv} + \Phi_2' Dung_{iv}\text{x}Hill_v + \Delta_3' X_{iv} + \Gamma_3' V_v + \varepsilon_{iv} \quad \textbf{(4)}$$

Because we use both the NLSS and Census data to conduct these analyses, the details of the covariates included in each stage vary slightly because of the questions asked in each type of survey. The details of included covariates are provided in Tables 2-5.

4.3 Forest Cover Analysis

In addition to looking at the impact of biogas on household fuelwood use, we also estimate the environmental impacts on a larger scale: the change over time in VDC forest cover relative to VDC area. This analysis uses the change in rate of VDC biogas use as the key independent variable. On average, the VDC population with biogas installations increased by approximately 3-4 percent within this period.

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[24] Robustness checks excluding the dung covariates yield similar results. Dung covariates are not included in the first stage as dung and wood together are perfectly collinear with biogas.

As with household biogas use, the rate of VDC biogas uptake is not random and is correlated with both observed and unobserved factors. These might include livelihood projects or forestry programs that could confound estimates. We therefore apply our biogas company branch-access IV strategy once again. However, instead of predicting household biogas in the survey year, we use two-stage least squares with our branch instrument predicting the change in biogas rate between 2001 and 2011. Again, we use the instrument interacted with the Hill region to obtain differential impacts by region. The household-level controls (Agg_v) and cooking fuel use ($Fuel_v$) are aggregated to the VDC level[25] and then differenced (between 2001 and 2011). Including the differenced VDC-level variables in the regressions accounts for the changes in household characteristics that occur over the study period and that may influence the outcome. $\boldsymbol{V}_v$ again represents the time-invariant and baseline VDC controls included in equations (5) and (6). $\Delta Forest_v$ is the inverse hyperbolic sine of the percent change in net forest cover from 2000-2012 (so coefficients can be interpreted as in a log-transformed dependent variable).

$$\Delta\%BG_v = \kappa_1 + \rho_{11}BRANCH_v + \rho_{12}BRANCH_v \text{x} Hill_v + \Omega'_{11}\Delta Fuel_v + \Omega'_{12}\Delta Fuel_v \text{x} Hill_v + \Phi'_1\Delta Agg_v + \Psi'_1\boldsymbol{V}_v + \nu_{1v} \quad \textbf{(5)}$$

$$\Delta\%BG_v \text{x} Hill_v = \kappa_2 + \rho_{21}BRANCH_v + \rho_{22}BRANCH_v \text{x} Hill_v + \Omega'_{21}\Delta Fuel_v + \Omega'_{22}\Delta Fuel_v \text{x} Hill_v + \Phi'_1\Delta Agg_v + \Psi'_1\boldsymbol{V}_v + \nu_{2v} \quad \textbf{(6)}$$

[25] Household characteristics that are binary variables are aggregated to the VDC-level as proportions of the VDC with that characteristic. Household characteristics that are continuous variables are aggregated to the VDC-level as averages for the VDC.

$$\Delta Forest_v = \alpha + \beta_1 \Delta \widehat{\%BG}_v + \beta_2 \Delta \widehat{\%BG}_v \text{x} Hill_v + \Omega'_{31} \Delta Fuel_v + \Omega'_{32} \Delta Fuel_v \text{x} Hill_v + \Phi'_3 \Delta Agg_v + \Psi'_3 \boldsymbol{V}_v + \varepsilon_v \tag{7}$$

If there are markets for fuelwood, biogas take-up may not affect forest cover. In the absence of constraints on collection or sales, fuelwood saved by biogas users may be collected and sold for consumption elsewhere. For this reason, we also look for differential effects of biogas in areas with forest protection policies, where these responses are likely to be limited by policy. We examine the presence of two policy types: protected areas (PAs) and community forest user groups (CFUGs) by interacting the measures of these forest protection policies with biogas.

5. Results

Within this section, we test for evidence consistent with possible indicators of the sustainable development potential of biogas. After providing empirical support for our instrumental variables, we test whether biogas reduces fuelwood both collected and purchased as well as time spent in collection. We then analyze impacts on household time allocation, including all major activities as well as more detailed categories within home production. Finally, we test whether changes in biogas installations impacted the rate of forest cover change.

Each table displays results from the tests of a set of hypotheses using a particular dataset (e.g. the census micro data, the NLSS household survey data, forest cover data). Testing multiple hypotheses with a single dataset can lead to concerns of Type I error (findings of false positives). Each table reports the standard errors without correction for multiple hypothesis and then also notes how to adjust the critical p-values according to the conservative Bonferroni correction (dividing the desired α by the number, n, of hypotheses tested).

5.1 Household level analyses

5.1.1 Support for instrumental variables

Table 1 shows the regression coefficients and Chi-squared test statistics for the joint significance of instruments *BRANCH* and *BRANCH*Hill* in each of the household-level first stage logit regressions described in equation (1). Columns 1 and 2 show the first stages for census households used in the analysis of male and female time-use (these are slightly different as some households have only one gender). Column 3 shows the first stage for the NLSS data used to analyze firewood collection. With values of 33.21 and 29.62 (p-value < 0.01 in both cases), the test statistics indicate that the instruments are jointly relevant and are reasonable predictors for the census sample.[26] However, the instruments are not as strong when applied to the NLSS data due to its smaller sample size.[27] The instrument is also a stronger predictor in the Hill than the Terai within the census sample but within the Terai for the NLSS sample.

Placebo test results are reported in Table 2. These examine whether our instrument predicts either the use of LPG (the other high-quality cooking fuel available to households) or electricity (the other main source of household energy). The dependent variable for these regressions is a binary variable for the choice of LPG as a cooking fuel vs. wood or dung. For these

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[26] Other papers that use this methodology and provide similar evidence for instrument relevance in this first stage include Adams et al. (2009), Nguyen et al. (2008), Guash et al. (2007), and Durrance (2010).

[27] Running the first stage using the census data limited to the NLSS 03/10 VDCs produces a Chi-squared statistic more similar to columns 1 and 2, suggesting it is an issue of sample size, not VDC selection.

specifications, the Chi-squared statistics are small and not significantly different from zero, meaning that our instrument does not strongly predict LPG use or electrification. These placebo test results suggest that our instrument successfully captures the expansion of biogas supply due to factors not correlated with LPG and electricity use, such as market access or household wealth.

We also use the Kleibergen-Paap rank Wald F-statistic as a test for weak instruments for the first stage of the two-stage least squares (reported in Tables 3, 4 and 6 with each set of results). This is similar to the Cragg-Donald F-statistic (which is equivalent to the normal F-statistic in the case of one endogenous regressor), but is robust to violations of conditional homoscedasticity. Although critical values for the Kleibergen-Paap have not been generated, it is standard to use the Stock-Yogo values (Stock and Yogo, 2005), which were developed for the Cragg-Donald statistic (see for example Bentzen, 2012 or Fishback et al, 2010). We indicate whether the test statistic is above the critical value for two-stage least squares maximal size distortions of 20%, 15% and 10%. All of our test statistics are above these critical values. In other words, if one is willing to accept a maximal weak instrument bias of 10%, the null hypothesis of weak instruments is rejected.

5.1.2 Fuelwood use savings and time savings

Table 3 presents both OLS[28] and IV results for household fuelwood collection based on the NLSS data from 2003 and 2010. We estimate different impacts for Terai and Hill regions

[28] We also used the Oster bounds (Oster 2016) to check for the strength of confounders needed to overturn the results. This indicated that such confounders were likely, providing additional support for using our instrumental variables as our primary empirical approach.

separately by interacting an indicator variable designating location in the Hill with the biogas variable. As a result, the impact of biogas in the Hill region is the sum of the coefficient on the biogas variable and the coefficient on the biogas*Hill interaction variable. We provide that sum in Table 3 to represent the effect of biogas in the Hill region.

Since households can either collect or purchase wood, we include measures of both collection and expenditure. How households get firewood varies considerably by region. In the Hill region, 94% of households collect wood and only 27% purchase wood; in the Terai, those numbers are 65% and 41%, respectively. The results from OLS with VDC fixed effects (Table 3, Panel B) suggest that across regions, biogas reduces the amount of fuelwood collected by approximately 800-950 kg per year, saves households 65-73 hours per year, and reduces expenditure by approximately 800-1100 NR (approximately 8.08-11.1 USD) per year.[29] Comparing the biogas effect to the mean values among households using firewood as their main fuel (83% of households in our sample), when a Terai household adopts biogas, they can expect to collect 51% less wood, spend 39% less time collecting it, and spend about 55% less money on it. For a household in the Hill region, those figures are approximately 30% less wood, 23% less time, and 86% less money. The percentage change impacts on wood collection (amount and time) in the colder Hill region are likely lower because biogas displaces a smaller share of total firewood, which is used for both cooking and heating. Also, it appears that Hill households (almost all of which collect some wood) use biogas to replace purchased wood before replacing collected

[29] Many households do not both collect and purchase fuelwood. Households that report no collection amount or no expenditure are coded as having a value of 0 for that variable.

wood. Although not significantly different from the OLS,[30] the IV results yield larger impacts: for instance, estimated savings in kg are approximately 1350-2000 kg. Time savings in the Terai increases to approximately 88 hours (or 47%) per year and in the Hill to 128 hours (or 46%) per year. This suggests that the OLS fixed effects results are likely a lower bound on the actual reductions in time saved. In addition, we note that our point estimates are similar overall to Somanathan and Bluffstone (2015), who find that biogas reduces firewood collection by 1100 kg/year.

5.1.3 Time use: home production

We use the much larger sample of census data to examine whether adopting biogas affects overall time use for different members of the household, as shown in Table 4.[31] In general, the IV results are similar but of larger magnitude than the OLS results.[32] The dependent variables in each case are the percent of months that household members reported spending on each type of activity within the last year. Coefficients in Table 4 are thus interpreted as a percentage point change due to adopting biogas. Using more detailed NLSS and NLFS time use data, we also sought to understand the channels through which biogas may specifically affect home production

[30] We tested for the endogeneity of regressors using the *endog* option of *ivreg2*, which tests the difference between the two Sargan-Hansen statistics. Unlike the Durbin-Wu-Hausman test, this test is robust to violations of conditional homoscedasticity. We fail to reject the null in all three of the firewood analyses, suggesting that for these outcomes, OLS and IV analyses give similar answers

[31] As a robustness check, we also perform this analysis dropping the top and bottom 1% of VDCs (according to size). Results do not substantially change.

[32] Testing for endogeneity using the same method as above, we find that 8/10 of the census outcomes reject the null at the 5% level and the other 2/10 reject at the 10% level.

(Table 5). These results use OLS with VDC fixed effects rather than our IV strategy[33], and thus should be taken as suggestive. Columns 1-5 and 7-11 are all components of "home production" in the census, while livestock care (columns 6, 12) is considered "agriculture".

Consistent with the NLSS results on fuelwood collection, we find that females spend less time on home production as a result of biogas; however, the analysis using census data indicates total time savings that are statistically significant and large only in the Terai region. Biogas in the Terai region reduces females' time spent in home production by 11 percentage points from a mean of 43%.[34] When we examine the more detailed data (Table 5), which reports the number of hours spent on each activity during the past week, we find that biogas is associated with a decrease in time spent collecting wood or dung in both regions. This finding supports our conclusions drawn from the firewood section of the survey. We also find that these changes are of greater magnitude for women than men: ranging from approximately 49 hours per year to 78 hours per year for women and 12 to 20 hours per year for men, explaining why females would be more likely to see a corresponding decrease in overall home production.

However, there is no statistically significant evidence that biogas households spend less time in cooking or cleaning, a benefit often expected of biogas. Although impacts are not significant, there are positive coefficients for females on water collection, cooking, and food processing time in the Hill region. This is consistent with the fact that water, which is a main input to biogas, is

[33] The IV strategy had a first stage that was too weak due to the smaller number of VDCs in the sample. Although the NLSS/NLFS sample includes more households than the NLSS II/III sample, there is more overlap among sampled VDCs, so the number of VDCs is lower.

[34] This is almost the same level as that in the Hill region (~30% of time).

more difficult to collect in the Hill region. Together these results suggest explanations for why home production decreases but not to a large or statistically significant extent for women in the Hill region.

Interestingly, males in the Terai with biogas spend more time (2.8 percentage points or 45% more time) on home production. This may reflect an increase in time spent on food preparation (Table 5) by men, due to the relative ease of cooking with biogas in comparison to traditional fuels. This is, however, speculative as the estimated changes in categories of home production are not statistically significant.

5.1.4 Time use: labor allocation

Households with biogas show significant shifts away from time spent in wage labor (in both regions), and possibly self-employment (in the Hill region). In the Terai, these decreases are matched with increases in agriculture and time in educational studies; whereas in the Hill, they are met by an increase in studies. There are several possible explanations for these shifts in time allocation. For example, amongst households previously purchasing wood, biogas adoption could alleviate liquidity constraints, thus allowing households to reallocate their time from activities that generate cash quickly to activities that potentially yield higher returns, albeit over a longer time horizon. This could also explain why households in the Terai shift away from wage labor much more than those in the Hill region: among wood-using households, 44% of Terai households purchase at least some wood while only 27% of Hill households do. Another explanation is that agricultural work is complementary to investments in biogas. This is plausible, both because biogas depends on keeping livestock (some of which are also used to plough fields) and because biogas produces a slurry byproduct that can be used as fertilizer. Households reallocated substantial time towards agriculture in the Terai (12-13 percentage points or an approximate doubling of time among controls). This is consistent with the potentially larger return to agriculture in the Terai compared to the Hill, due to a higher focus on commercial crops rather than subsistence agriculture, and a general increase in agricultural productivity driven by increased access to irrigation and more effective fertilizer practices (Marquardt, Khatri and Pain, 2016).

5.1.5 Time use: education

In addition to changes in labor allocation, we find significant increases in the time spent on education across gender and regions for the household as a whole. According to our IV results, biogas causes households to increase the time spent on education by 4-11 percentage points (25-40% from the means of 20% among females and 27% among men). These household aggregates include all members 10 and older, but we interpret them as pertaining mainly to adult household members, given that a test of the IV results for the group aged only between 10-18 years old did not show corresponding significant increases in study time.[35] Nepal has run a series of adult education programs, generally focusing on adult literacy and on functional/vocational skills (Regmi 2016). These programs are often conducted at night and implemented in rural areas. In the 2000's, these adult education programs were supported under Nepal's "Non-Formal

[35] As described in the data section, the census collected data on economic and non-economic activities of each family member, aged ten years or higher. A test looking separately just at the time allocation of the group aged between 10 and 18 years old did not find a significant increase in study time, and in fact showed conflicting results between the OLS and IV specifications, with the IV implying possibly significant negative impacts on time spent studying and more time on home-production. This may be due to heterogeneity in treatment effects as well as the already high proportion of time spent studying by most teenagers during this time. According to the UNICEF MICS surveys in 2010 and 2014, secondary school net attendance increased from 55.6% to 62.3% over our study period (UNICEF MICS, 2012; UNICEF MICS, 2015).

Education Center" with substantial support from multilateral institutions (UNESCO 2006, GON 2007).

5.2 VDC level analyses: forest cover

The substantial reduction in fuelwood use among biogas households suggests that forest cover could increase over time in areas with higher rates of biogas use. This is not necessarily the case for multiple reasons. Other (non-biogas) households might increase collection, potentially offsetting reductions amongst the biogas households. Also, firewood may primarily affect forest quality rather than forest cover. Yet the relationship between biogas penetration and forest cover clearly remains a question worth examining.

Rates of deforestation within Nepal as a whole were substantial during the 2000-2012 period; however, they were much lower than that of the 1990's. In our study of VDCs during this time, the Terai areas on average lost forest cover equivalent to about 0.4% of total area, whereas the Hill areas gained about 0.5% of forest cover on average. Measured in comparison to initial estimated forest cover, both showed average gains, with about 5% in the Terai and 1.4% in the Hill. These values reflect both the uneven distribution of forest cover change and the generally larger baseline proportion of forest cover in the Hill (about 50%) versus Terai (about 25%), on average. Although most of the distribution of forest cover change is clustered around very small changes, about 5% of the Hill VDCs deforested 1% or more, or reforested 2% or more; and about 5% of the Terai VDCs deforested 2.5% of area or more. In addition, the majority of Terai VDCs showed net forest loss during this period. Taken together, this indicates that loss of forest remains a problem in many areas of Nepal.

Table 6 shows results of our estimated OLS and IV impacts of biogas on net forest cover change as well as the first stage test statistics. Given the dependent variable of net forest cover change, positive coefficients indicate less forest cover loss (or more forest cover gain) relative to the counterfactual. Since values of the dependent variable are transformed with the inverse hyperbolic sine, magnitudes can be interpreted as with a standard log-linear regression. The table shows estimates for net forest cover change relative to both baseline area and to original forest cover area. The estimates relative to baseline area are likely more reliable as they are less influenced by outliers[36], but the estimates relative to baseline forested area report changes in terms of deforestation rates as they are more commonly calculated.

To some extent, biogas initiatives may have been targeted to areas that had recently lost forest cover or could have been part of larger initiatives promoting sustainable forest use. The goal of our IV strategy is to overcome bias due to selection, omitted variables, or simultaneity. From the main IV results (Table 6, Panel B, columns 1 and 2), we find that biogas installations have had a positive and statistically significant impact in the Hill region.[37] A one percentage point increase in biogas users resulted in an approximately 5.4 percent increase in forest cover change, compared to baseline area ("Hill effect"). To put this number in context, consider a VDC that is about 3000 ha in size (the actual average is 3277 ha) and gained about 4 percentage points of biogas installations (the actual average is 3.6 percent) over this period. If this VDC were

[36] This would be due to apparent large percentage changes resulting from areas with very little forest cover to start.
[37] Stock-Yogo critical values have not been tabulated for cases with more than two endogenous variables. Therefore, we also include the first stage Sanderson-Windmeijer F statistics testing for weak identification of each endogenous regressor, all of which exceed the critical values.

expected to lose 1% of forest cover as a percent of area during this period, that would mean losing 30 ha of forest cover. So, if biogas lead to a 5.4 percent reduction, that would mean ~5.4 percent * 4 * 30 ha or about 6.5 ha of avoided deforestation in this VDC. For a VDC with about 900 households (close to the median), that would correspond to the change associated with approximately 30-40 more households that had received biogas installations.

The IV results in the Terai ("change in % biogas") are approximately zero for the area-based changes due to biogas installations. They are possibly negative for the baseline-forest based changes, potentially consistent with an expansion of agricultural activities as a complement to biogas in the Terai. Firewood markets could also provide a reason as to why the results differ between Hill and Terai. In Nepal, very few markets exist in the Hill areas because of transportation difficulties. In contrast, wood is more frequently purchased from different locations in the Terai and freely functioning markets would distribute any forest impacts across space, making effects undetectable (for an example in Mexico, see e.g. Alix-Garcia et al. 2013).[38]

In columns 3-6, we test whether biogas can improve forest cover when complemented by particular forest management policies. Table 6 shows both the coefficients on the interaction terms for forest policy ("Biogas*Forest Policy") and the total effect implied by summing the main and interaction terms ("Forest Policy Effect-Terai" and "Forest Policy Effect-Hill"). We find that in combination with protected areas in the Hill regions, the impact of biogas increases

[38] An alternative reason for small estimates is that neighboring households respond by collecting additional wood. For this reason, we tested for spillovers to other households without biogas in VDCs with high uptake of biogas. We did not find significant increases on average wood collection by neighboring households.

to approximately 10.9 percent. In combination with community forest user groups, it increases to about 6.1 percent. Estimated impacts of biogas in conjunction with forest policies in the Terai are 5.5 percent for protected areas and 1.4 percent for community forest user groups; however, these are not statistically significant.

Together, these results indicate a potential for biogas to deliver positive forest cover benefits and highlight that these impacts are likely greater when paired with other policies managing forest access. In addition, the forest cover changes that can be attributed to biogas installations in Nepal are small to moderate in magnitude. This is due to both the relatively low penetration of biogas as well as the small average changes in Nepal's forest cover during the most recent decade. Impacts could be substantially higher if biogas were installed at more households, or if forest cover loss returned to high levels. The ICIMOD data indicates that our study VDCs lost approximately 5% of forest cover on average as a percentage of area between 1990 and 2000. The higher deforestation rate typical of Nepal in the past could return in the future, particularly if the rate of Nepalis' economic migration to international destinations slows (Oldekop et al. 2017b).

6. Conclusion

Renewable energy technologies, such as biogas, are likely to be an important part of global efforts to improve energy access and standards of living for current generations without compromising the welfare of future generations. With developing countries on track to consume more energy than OECD countries by 2040 (U.S. Energy Information Administration 2016), potential win-win technologies are key to achieving sustainable development goals. This study represents one of the first attempts to rigorously measure the sustainable development potential of a key renewable energy technology.

Indeed, institutions such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Clean Development Mechanism (CDM) of the Kyoto Protocol have strongly promoted household biogas. To date, there have been more than four million installations in India and 27 million in China. Yet significant potential for additional future biogas installations remains: estimates indicate potential for up to 17 million household systems in India and a doubling of China's household systems (Chen et al. 2010, Bond and Templeton 2011). In Nepal, the 300,000 systems installed by 2015 are estimated to be only 29% of households that are well-suited for biogas[39] (BSP, 2012). Yet before continuing major investments in this technology, or other renewable energy technologies, it is important to understand their impacts and the other policies or conditions that may interact with the technology.

Previous literature on biogas found a significant decrease in fuelwood use among biogas households, but did not answer whether these savings translated to measurable improvements in the household's time allocation or the local environment. Our findings support these results, and suggest that they may even underestimate the true impact of biogas on fuelwood use in Nepal. We find evidence that the impact of biogas on labor allocation is substantial, with shifts away from home production and wage work into agricultural effort and educational time. If these shifts

[39] A study of technical potential of biogas in Nepal suggests 1.03 million suitable households who have not yet installed biogas (SETM, 2013).

generate a higher economic return on time for households, then they are likely to improve household welfare in the short term. If they represent productive investments in physical and human capital then they also have the potential to contribute to long-term development. Yet such gains are not a given; they will depend on the economic opportunities available to households, both locally and on a national or global scale. That many people in Nepal currently lack strong economic opportunities, especially in rural areas, may explain why adult household members reallocate time to education and learning new skills. For these investments to pay off and translate into sustainable improvements in income, there must be higher wage opportunities available for more skilled workers over the long run. Our results on fuelwood use and forest cover do suggest positive environmental gains due to biogas adoption, particularly in the hill areas. Overall impacts are moderate, likely due to the low overall rates of forest change during this period. However, we do find greater impacts in the presence of forest protection policies, again highlighting the importance of complementary conditions for the success of biogas.

In summary, we find that biogas has positive potential to deliver both socio-economic and environmental improvements today and in the future, but that these results may require complementary factors such as high-return labor options and forest protection policies to facilitate substantial shifts towards long-term sustainable development.

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Figure 1. Percent of households with biogas installed per VDC

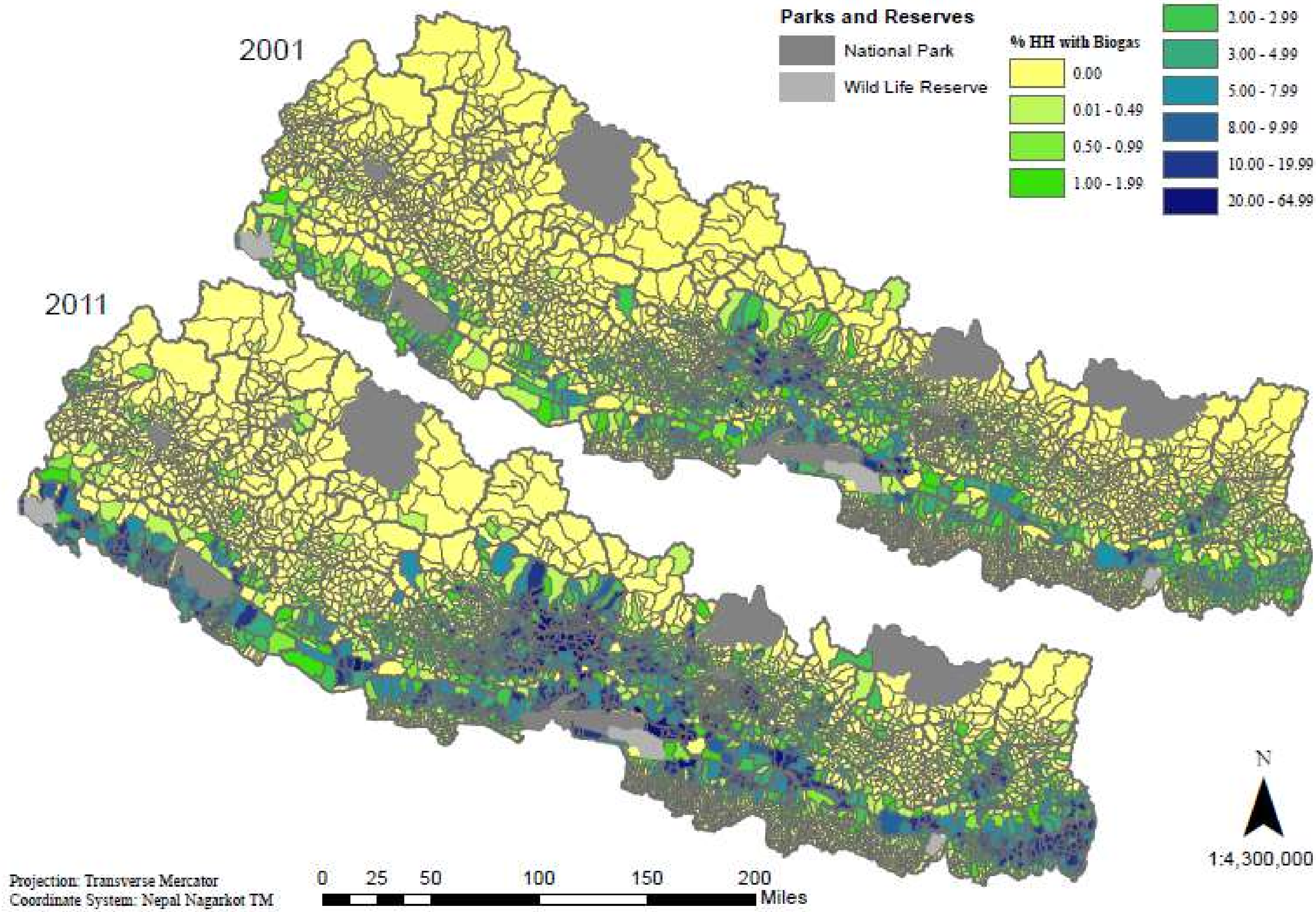
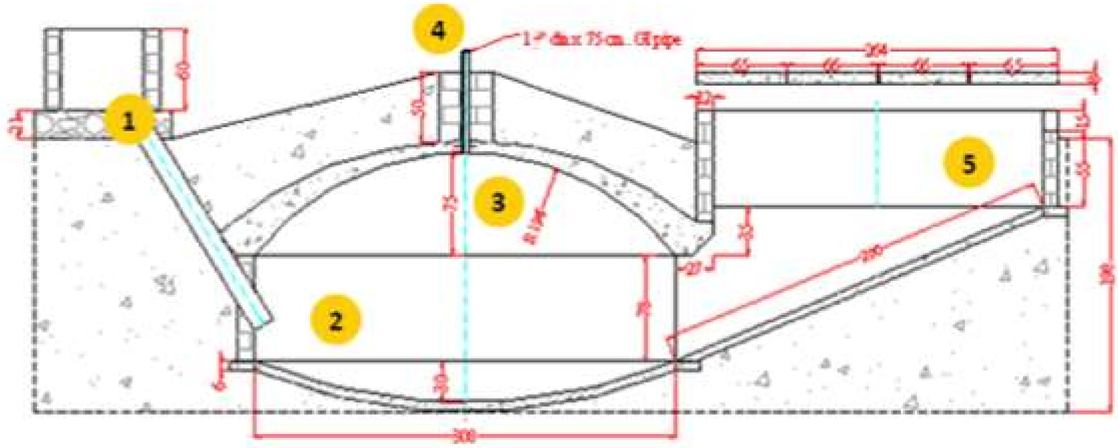


Figure 2a. Blueprint of a 10m^3 biogas digester model GGC2047.



Key: (1) Inlet chamber with inlet pipe; (2) Digester; (3) Dome (gas storage); (4) Gas outlet; (5) Bioslurry overflow (Lohri et al., 2010)

Figure 2b. Finished biogas system (Bajgain et al., 2005)

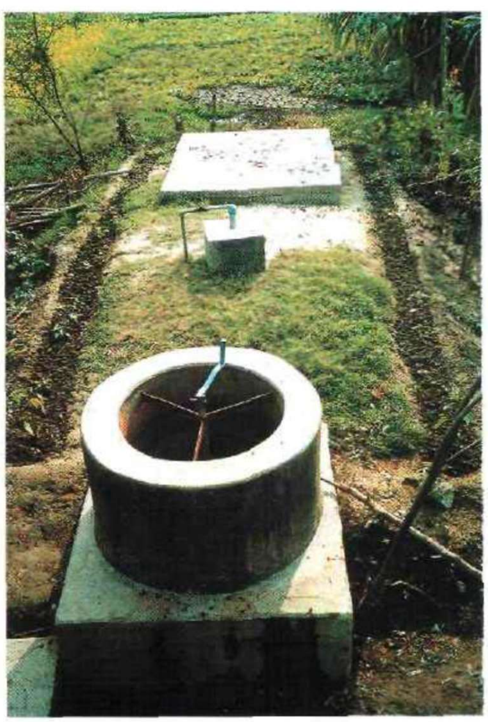


Photo 1.2: Biogas system

Figure 3. Less penetrated districts

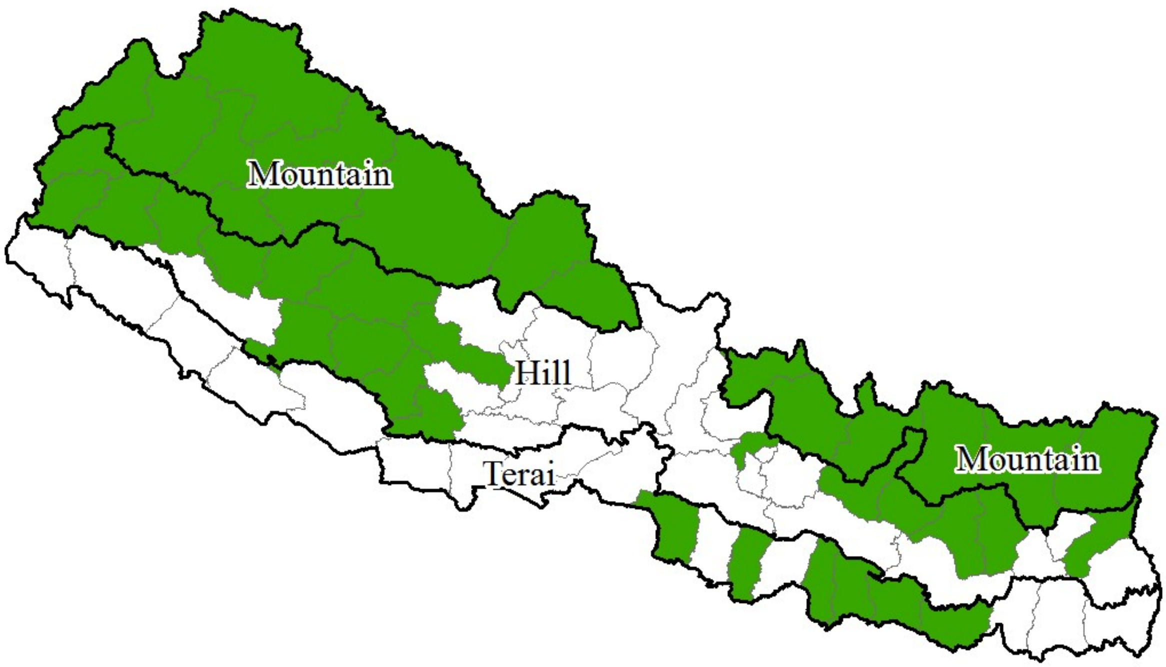


Figure 4. Biogas Branches and Market Access

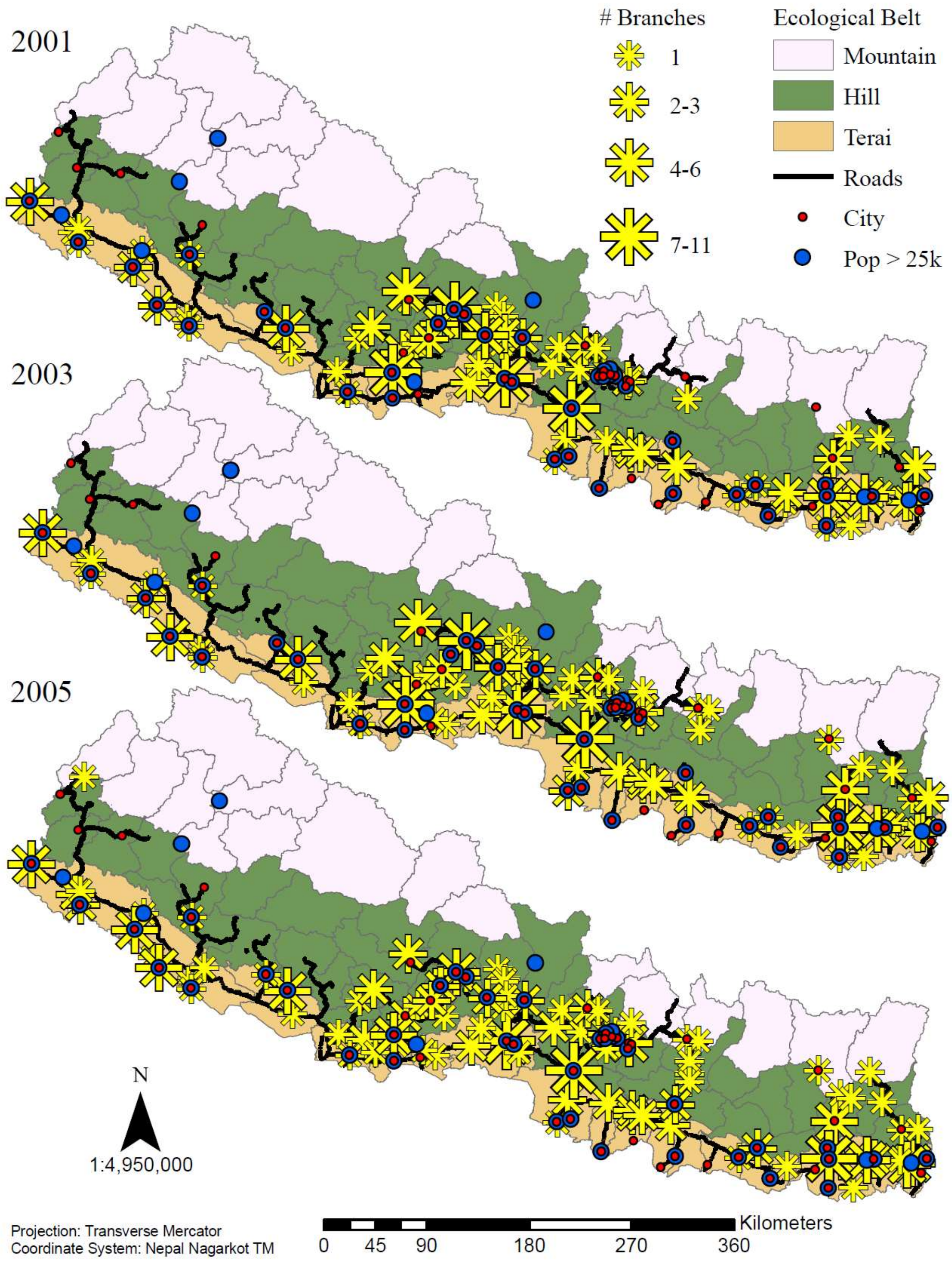


Figure 4 (continued). Biogas Branches and Market Access

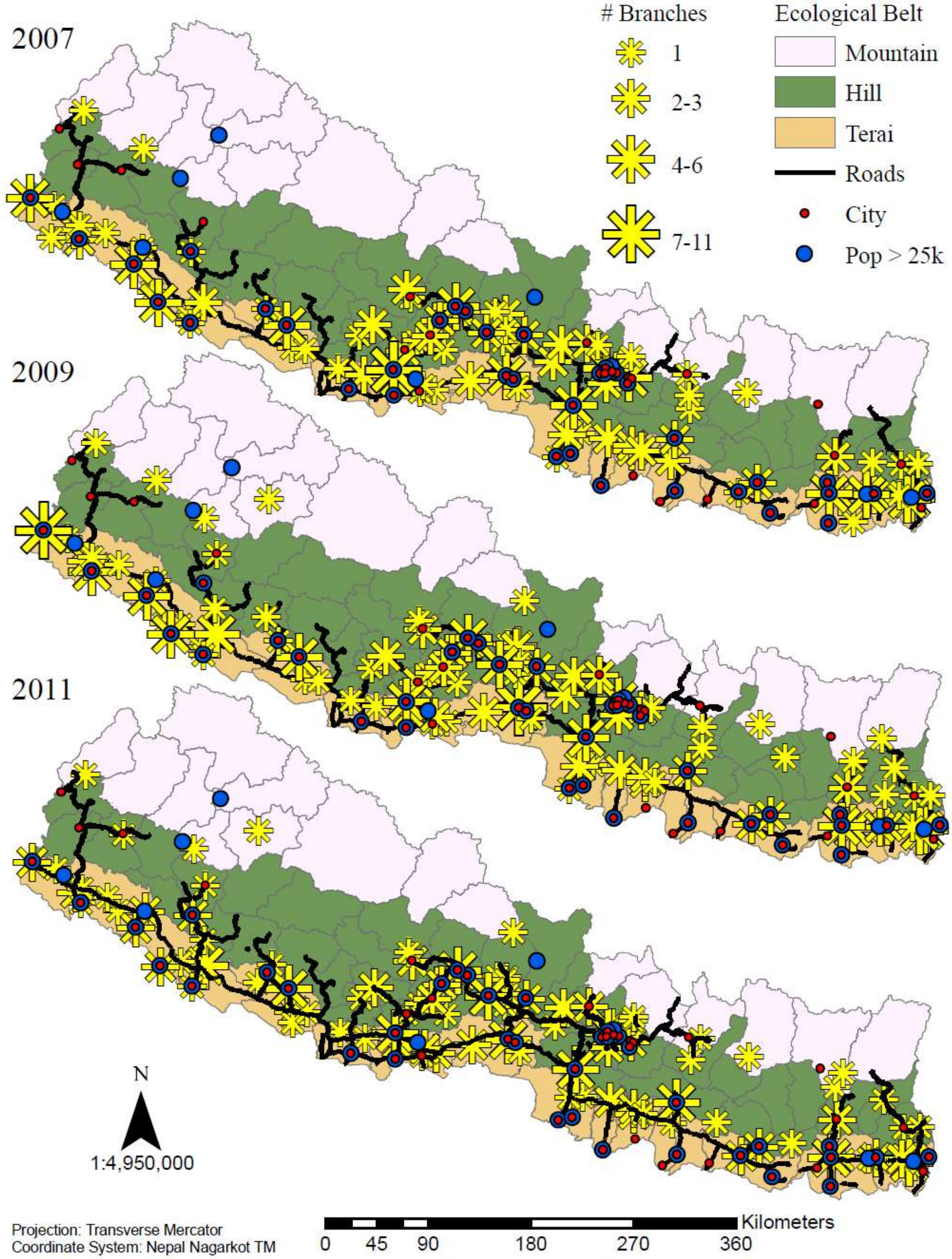
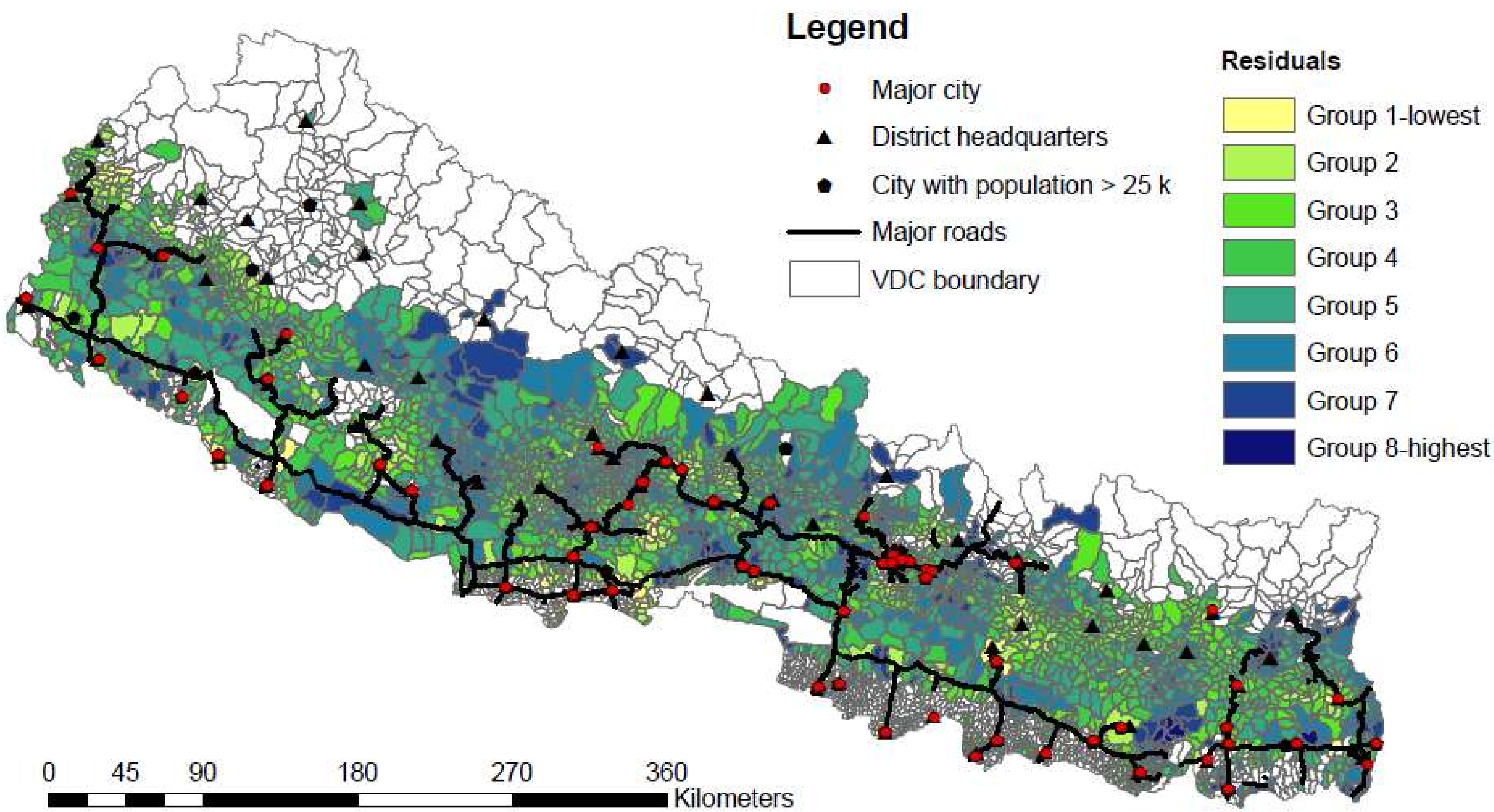


Figure 5. Variation in distance to biogas branches used to instrument for adoption



Notes: Map shows the residuals from a regression of average distance to biogas company location on all other included controls. Residuals thus indicate the remaining variation in distance that is used to instrument for biogas adoption and identify impacts.

Table 1. First stage logit regressions predicting household biogas use

	Census (2011)		NLSS II/III (2003, 2010)
	Male	Female	
	1	2	3
Logged Branch distance	-0.109	-0.107	-0.602**
	(0.088)	(0.088)	(0.196)
Logged Branch distance*Hill	-0.420***	-0.400***	0.111
	(0.092)	(0.094)	(0.197)
2001 Logged Branch distance	0.137*	0.135*	0.495***
	(0.063)	(0.064)	(0.142)
Household characteristics			
Electrified	✓	✓	✓
Owns home	✓	✓	✓
Piped water	✓	✓	✓
Toilet	✓	✓	✓
Radio	✓	✓	
Mobile phone			✓
TV	✓	✓	✓
Ethnicity	✓	✓	✓
Household head education	✓	✓	✓
Household size (by age groups)	✓	✓	✓
Land owned (hectares)			✓
Wood collection location			✓
Number of cow/buffalo			✓
Logged per capita income			✓
VDC characteristics	✓	✓	✓
2001 VDC aggregates of HH characteristics	✓	✓	✓
Year fixed effects			✓
Chi-Squared test of joint significance	33.21	29.62	9.50
P-value	0.00	0.00	0.01
VDC clusters	2736	2736	530
Observations	392,786	435,297	6,649

Notes: Census households are considered biogas households if it is their main cooking fuel. NLSS households are considered biogas households if it is their main cooking fuel OR they produce any biogas at home. Household samples include households using biogas, dung, or wood as cooking fuel. Includes all VDCs from Terai and Hill region as well as 190 VDCs from the mountain region that had at least one biogas plant installed by 2011. Sample limited to VDCs with >10 hectares forest cover and >1% forest cover in 2001. VDC controls: proportion of 2001 households in VDC with female land ownership, migrant in the household, involvment in agriculture, own business, owning land, owning livestock, average number of livestock, and main fuel being dung, wood, and LPG/kerosene; VDC area, elevation, slope, annual precipitation, 2001 population, change in population 2001-2011, and region; having at least 25k and 50k inhabitants; distance to Kathmandu, the neareast road, the nearest municipality, and the nearest pop centers of 25k and 50k; proportion of forest cover under CFUG management in pre-2001 and post-2001; the proportion of protected forest cover, and distance to the nearest biogas branch in 2001. Standard errors are clustered at the VDC-level. *, **, *** indicate significance at the 10%, 5%, and 1% level, respectively. Chi-squared results (and associated p-values) are the tests of joint significance for instruments.

Table 2. Placebo tests: Instrumental variables and household use of other energy sources

	Census (2011)		NLSS II/III (2003, 2010)
	Male	Female	
	(1)	(2)	(3)
Panel A: Placebo Test using LPG			
IV	0.124	0.101	-0.107
	(0.085)	(0.087)	(0.142)
IV*hill	-0.099	-0.085	-0.242
	(0.089)	(0.089)	(0.152)
Chi-Squared	2.20	1.43	3.83
P-value	0.33	0.49	0.15
VDC clusters	2736	2736	527
Observations	481,795	530,732	7,507
Panel B: Placebo Test using Electrification			
IV	0.018	0.011	0.266
	(0.109)	(0.109)	(0.161)
IV*hill	0.023	0.029	-0.287
	(0.095)	(0.096)	(0.163)
Chi-Squared	0.20	0.22	-0.29
P-value	0.90	0.89	0.16
VDC clusters	2736	2736	533
Observations	505,958	555,102	8,375

Notes: Household samples report chi-squared test of joint significance of instruments (branch and branch*hill). Census households considered biogas if main cooking fuel is biogas. NLSS/NLFS households are considered biogas households if it is their main cooking fuel OR they produce any biogas at home. LPG refers to main cooking fuel. Branch distance is the logged average Euclidean distance to nearest branch between 2002 and 2011. Household samples include households using biogas, dung, or wood as cooking fuel. LPG placebo test replaces biogas households with LPG households. Electricity placebo test uses all households. The omitted group is wood. Includes all VDCs from Terai and Hill region and 190 mountain VDCs with any biogas installations by 2011. Census analysis limited to VDCs with >10 hectares forest cover and >1% forest cover in 2001. Each sample includes the covariates listed in the results table for that sample.

Table 3. Impacts of biogas on household firewood collection and purchase

	Annual Wood Collection		Expenditure
	Kilograms	Minutes	2010 NR
	(1)	(2)	(3)
Panel A: OLS			
Biogas in Terai	-1105.0***	-4758.5***	-963.9***
	(135.70)	(810.70)	(205.50)
Biogas in Hill	-946.9***	-5000.3***	-793.9***
(Biogas + Biogas*Hill)	(150.93)	(719.05)	(213.96)
Panel B: OLS with VDC Fixed Effects			
Biogas in Terai	-943.2***	-4405.3***	-1106.5***
	(146.40)	(928.40)	(210.70)
Biogas in Hill	-794.6***	-3917.1***	-818.8***
(Biogas + Biogas*Hill)	(124.76)	(691.18)	(232.54)
Panel C: IV			
Biogas in Terai	-1965.2***	-5301.0*	-923.3
	(435.10)	(2347.10)	(608.50)
Biogas in Hill	-1354.4***	-7692.1***	-1415.9**
(Biogas + Biogas*Hill)	(388.68)	(2277.67)	(569.79)
First Stage Kleibergen-Paap F	178.3 †††	178.3 †††	178.3 †††
Mean dep. var. - Terai	1,847	11,235	2,024
Mean dep. var. - Hill	2,778	16,782	946
VDC clusters	530	530	530
Observations	6,649	6,649	6,649

Notes: Outcome variables are from the Nepal Living Standards Survey 2003 and 2010. Top 1% of outcome measures Windsorized. Households are considered biogas households if it is their main cooking fuel OR they produce any biogas at home. Dung refers to main cooking fuel. Omitted group is wood ans the means of dependent variables are calculated for the omitted group. Households using other fuel types are excluded. Includes all VDCs from Terai and Hill region and 31 mountain VDCs with any biogas plants installed by 2011. All columns control for VDC and year fixed effects as well as household and VDC controls. Household controls: asset ownership (home, piped water, electricity, toilet, radio, TV), ethnicity, household head education, household size separated by age (0-9, 10-17, 18+), land and livestock ownership, per capita consumption, dung as main fuel source, location of firewood collection, and month of interview. VDC controls: proportion of 2001 households in VDC with electricity, piped water, tv female land ownership, migrant in the household, involvement in agriculture, own business, head with high school education, household size in each age category, ethnicity, owning land, owning livestock, average number of livestock, and main fuel being dung, wood, and LPG/kerosene; VDC area, elevation, slope, annual precipitation, 2001 population, change in population 2001-2011, and region; having at least 25k and 50k inhabitants; distance to Kathmandu, the nearest road, the nearest municipality, and the nearest pop centers of 25k and 50k; proportion of forest cover under CFUG management in pre-2001 and post-2001; and the proportion of protected forest cover. Standard errors clustered at VDC level. Standard errors clustered at VDC level. *, **, *** indicate p-values less than 10%, 5%, and 1%, respectively. Bonferroni adjusted values of the critical p-value would be $\alpha/3$. †, ††, ††† indicate TSLS size distortions of a maximum of 20%, 15%, and 10%, respectively.

Table 4. Impacts of biogas on percent of months household members spent on each activity in last year

	Men					Women				
	Home Production	Studies	Agriculture	Wage	Self-Employment	Home Production	Studies	Agriculture	Wage	Self-Employment
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: OLS										
Biogas in Terai	0.493*	1.847***	6.027***	-8.042***	-0.263	-2.460***	1.154***	4.353***	-2.617***	-1.154***
	(0.225)	(0.371)	(0.580)	(0.590)	(0.286)	(0.470)	(0.281)	(0.500)	(0.267)	(0.161)
Biogas in Hill	-0.272	2.077***	-0.796	-0.167	-0.516*	0.916	0.755***	-0.265	-0.294	-0.681***
(Biogas + Biogas*Hill)	(0.266)	(0.455)	(0.579)	(0.527)	(0.299)	(0.593)	(0.268)	(0.583)	(0.260)	(0.207)
Panel B: IV										
Biogas in Terai	2.753**	10.96***	13.29***	-31.84***	0.7304	-11.20***	5.435***	12.05***	-11.32***	-0.509
	(1.024)	(1.445)	(2.557)	(2.711)	(1.085)	(1.961)	(1.044)	(2.242)	(1.200)	(0.698)
Biogas in Hill	1.036	5.734***	1.250	-7.359**	-2.928*	-1.584	4.795***	0.222	-2.806*	-1.869*
(Biogas + Biogas*Hill)	(1.165)	(2.061)	(3.306)	(3.363)	(1.643)	(3.178)	(1.664)	(3.419)	(1.437)	(1.001)
First Stage Kleibergen-Paap F	345.5 †††	345.5 †††	345.5 †††	345.5 †††	345.5 †††	344.2 †††	344.2 †††	344.2 †††	344.2 †††	344.2 †††
Mean dep. var. - Terai	6.23	26.39	27.16	23.41	7.45	42.70	19.80	20.57	6.51	3.64
Mean dep. var. - Hill	8.85	26.96	31.85	16.11	6.22	29.98	20.00	35.10	4.21	3.84
VDC clusters	2,736	2,736	2,736	2,736	2,736	2,736	2,736	2,736	2,736	2,736
Observations	392,786	392,786	392,786	392,786	392,786	435,297	435,297	435,297	435,297	435,297

Notes: Outcome variables are from the 2011 census microdata and are aggregated across all male/female members of the household 10 and older. Includes households using biogas, dung, and wood as their main fuel type. Omitted group is wood. Means of dependent variables are calculated for the omitted group. Includes all VDCs from Terai and Hill region as well as 190 VDCs from the mountain region that had at least one biogas plant installed by 2011. Sample limited to VDCs with >10 hectares forest cover and >1% forest cover in 2001. All columns control for household and VDC controls. Household controls: asset ownership (home, piped water, electricity, toilet, radio, TV), ethnicity, household head education, household size separated by age (0-9, 10-17, 18+), and dung as main fuel source. VDC controls: proportion of 2001 households in VDC with electricity, piped water, TV female land ownership, migrant in the household, involvement in agriculture, own business, head with high school education, household size in each age category, ethnicity, owning land, owning livestock, average number of livestock, and main fuel being dung, wood, and LPG/kerosene; VDC area, elevation, slope, annual precipitation, 2001 population, change in population 2001-2011, and region; having at least 25k and 50k inhabitants; distance to Kathmandu, the nearest road, the nearest municipality, and the nearest pop centers of 25k and 50k; proportion of forest cover under CFUG management in pre-2001 and post-2001; the proportion of protected forest cover, and distance to the nearest biogas branch in 2001. Standard errors clustered at VDC level. *, **, *** indicates p-values less than 10%, 5%, and 1%, respectively. Bonferroni adjusted values of the critical p-value would be α/5. †, ††, ††† indicate TSLS size distortions of a maximum of 20%, 15%, and 10%, respectively.

Table 5. Impacts of biogas on hours household spent in past 7 days on home production

	Men						Women					
	Wood/Dung Collection	Water Collection	Cooking	Cleaning	Food Processing	Livestock Care	Wood/Dung Collection	Water Collection	Cooking	Cleaning	Food Processing	Livestock Care
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Panel A: OLS												
Biogas in Terai	-0.0909	-0.137	-0.278	0.0275	0.291	2.051	-1.441***	-0.315	-0.164	1.044*	0.66	-0.234
	(0.272)	(0.084)	(0.219)	(0.187)	(0.157)	(1.781)	(0.405)	(0.245)	(0.538)	(0.442)	(0.337)	(1.821)
Biogas in Hill	-0.513**	-0.012	0.135	-0.205	-0.030	-0.760	-0.940**	0.422	0.609	0.374	0.146	-0.499
(Biogas + Biogas*Hill)	(0.244)	(0.207)	(0.325)	(0.197)	(0.072)	(1.591)	(0.392)	(0.463)	(0.651)	(0.502)	(0.313)	(1.751)
Panel B: OLS with VDC FE												
Biogas in Terai	-0.235	-0.129	-0.287	-0.0522	0.278	1.413	-1.500***	-0.214	-0.0794	0.825*	0.56	0.268
	(0.235)	(0.073)	(0.247)	(0.190)	(0.166)	(1.721)	(0.420)	(0.215)	(0.545)	(0.377)	(0.324)	(1.995)
Biogas in Hill	-0.390**	-0.134	-0.165	-0.298	0.064	0.862	-0.937**	0.427	0.131	-0.011	0.380	-0.085
(Biogas + Biogas*Hill)	(0.191)	(0.169)	(0.345)	(0.217)	(0.064)	(1.781)	(0.364)	(0.396)	(0.650)	(0.520)	(0.315)	(1.990)
Mean dep. var. - Terai	1.27	0.30	1.26	1.17	0.33	10.65	3.41	1.08	17.42	12.17	1.44	17.53
Mean dep. var. - Hill	2.36	1.62	2.09	1.66	0.60	17.44	4.57	3.79	16.70	12.30	3.32	25.76
VDC clusters	421	421	421	421	421	340	421	421	421	421	421	340
Observations	13,086	13,086	13,086	13,086	13,086	3,555	13,625	13,625	13,625	13,625	13,625	3,749

Notes: Outcome variables are from the Nepal Living Standards Survey 2010 and Nepal Labour Force Survey 2008 and aggregated across all male/female members 10 and older. Households are considered biogas households if it is their main cooking fuel OR they produce any biogas at home. Dung refers to main cooking fuel. Omitted group is wood. Means of dependent variables are calculated for the omitted group. Households using other fuel types are excluded. Omitted group is wood. The means for the dependent variables are for the omitted group. Includes all VDCs from Terai and Hill region and 14 mountain VDCs with any biogas installations by 2011. All columns control for VDC and year fixed effects as well as household and VDC controls. Household controls: asset ownership (home, piped water, electricity, toilet, radio, TV), ethnicity, household head education, household size separated by age (0-9, 10-17, 18+), dung as main fuel source, land ownership, location of fuel collection, per capita consumption, and month of interview. Livestock regression includes number of large livestock. VDC controls: proportion of 2001 households in VDC with electricity, piped water, TV female land ownership, migrant in the household, involvement in agriculture, own business, head with high school education, household size in each age category, ethnicity, owning land, owning livestock, average number of livestock, and main fuel being dung, wood, and LPG/kerosene; VDC area, elevation, slope, annual precipitation, 2001 population, change in population 2001-2011, and region; having at least 25k and 50k inhabitants; distance to Kathmandu, the nearest road, the nearest municipality, and the nearest pop centers of 25k and 50k; proportion of forest cover under CFUG management in pre-2001 and post-2001; and the proportion of protected forest cover. Standard erros clustered at VDC level. Standard errors clustered at VDC level. *, **, *** indicate p-values less than 10%, 5%, and 1%, respectively. Bonferroni adjusted values of the critical p-value would be α/6.

Table 6. Impacts of biogas on change in percent of VDC forest cover relative to VDC area

			Policy: Protected Areas		Policy: CFUG pre 2001	
	Relative to VDC area	Relative to 2000 Forest Cover	Relative to VDC area	Relative to 2000 Forest Cover	Relative to VDC area	Relative to 2000 Forest Cover
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS						
Change in % biogas	-0.003	0.007	-0.005	0.002	-0.004	0.005
	(0.005)	(0.013)	(0.005)	(0.013)	(0.005)	(0.014)
Change in % biogas*Hill	0.005	-0.002	0.005	-0.003	0.005	-0.004
	(0.005)	(0.013)	(0.005)	(0.013)	(0.005)	(0.013)
Biogas*Forest Policy			0.0233***	0.0513***	0.003	0.005
			(0.006)	(0.013)	(0.004)	(0.009)
Hill effect (%biogas + %biogas*Hill)	0.0024	0.0042	0.0003	-0.0005	0.0010	0.0015
	(0.002)	(0.003)	(0.002)	(0.003)	(0.003)	(0.006)
Forest Policy Effect - Terai			0.018**	0.054***	-0.001	0.010
(biogas + biogas*policy)			(0.007)	(0.017)	(0.005)	(0.013)
Forest Policy Effect - Hill			0.0236***	0.0509***	0.0037	0.0065
(biogas + biogas*hill + biogas*policy)			(0.0054)	(0.0127)	(0.0026)	(0.0051)
Panel B: IV						
Change in % biogas	0.001	-0.144*	0.001	-0.145*	-0.007	-0.170*
	(0.025)	(0.070)	(0.025)	(0.068)	(0.027)	(0.076)
Change in % biogas*Hill	0.0527*	0.216***	0.0534**	0.218***	0.0476*	0.200***
	(0.021)	(0.058)	(0.021)	(0.057)	(0.020)	(0.058)
Biogas*Forest Policy			0.0544**	0.108*	0.021	0.0661**
			(0.020)	(0.044)	(0.011)	(0.025)
Hill effect (%biogas + %biogas*Hill)	0.0538***	0.0721**	0.0542***	0.0730**	0.0403**	0.0298
	(0.016)	(0.032)	(0.016)	(0.032)	(0.018)	(0.037)
Forest Policy Effect - Terai			0.0552*	-0.0370	0.0137	-0.1044
(biogas + biogas*policy)			(0.029)	(0.076)	(0.024)	(0.068)
Forest Policy Effect - Hill			0.1086***	0.1805***	0.0614***	0.0959***
(biogas + biogas*hill + biogas*policy)			(0.0238)	(0.0524)	(0.0157)	(0.0326)
First stage Sanderson-Windmeijer F						
Δbiogas	27.34 †††	27.34 †††	27.84 †††	27.84 †††	28.25 †††	28.25 †††
Δbiogas*hill	55.98 †††	55.98 †††	56.00 †††	56.00 †††	58.312 †††	58.312 †††
Δbiogas*policy			78.15 †††	78.15 †††	186.65 †††	186.65 †††
First stage Kleibergen-Paap F	15.01 †††	15.01 †††	10.30^	10.30^	10.23^	10.23^
Mean proportion forest change - in Terai	-0.004	0.051	-0.004	0.051	-0.004	0.051
- in Hill	0.005	0.014	0.005	0.014	0.005	0.014
Observations	2736	2736	2736	2736	2736	2736

NOTE: Outcome variables and represent the inverse hyperbolic sine of the percent of forest cover change between 2001 and 2012 (positive values = increase in forest cover). Percent change is relative to either VDC area or original forest cover. The top and bottom 1% of values have been Windsorized. VDCs from the Hill, Terai, and mountain with at least one biogas plant installed by 2001; with >10 hectares forest cover and >1% forest cover in 2000. Controls: proportion of 2001 households in VDC with electricity, piped water, tv female land ownership, migrant in the household, involvment in agriculture, own business, head with high school education, household size in each age category, ethnicity, owning land, owning livestock, average number of livestock, and main fuel being dung, wood, and LPG/kerosene; VDC area, elevation, slope, annual precipitation, 2001 population, change in population 2001-2011, and region; having at least 25k and 50k inhabitants; distance to Kathmandu, the neareast road, the nearest municipality, and the nearest pop centers of 25k and 50k; proportion of forest cover under CFUG management in pre-2001 and post-2001; the proportion of protected forest cover, and distance to the nearest biogas branch in 2001. Standard errors clustered at VDC level. Standard errors clustered at VDC level. Standard errors clustered at VDC level. *, **, *** indicate p-values less than 10%, 5%, and 1%, respectively. Bonferroni adjusted values of the critical p-value would be $\alpha/6$. †,††, ††† indicate TSLS size distortions of a maximum of 20%, 15%, and 10%, respectively (for single endogenous or multiple endogenous regressors as appropriate). ^ indicates Stock-Yogo values not tabulated.