Variability in household energy use among smallholder farmers in rural Zambia

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Submitted to the faculty of the University Graduate School in partial fulfillment of the requirements for the degree

Master of Science

in the Department of Geography,

Indiana University

June , 2017

Accepted by the Graduate Faculty, Indiana University, in partial fulfillment of the requirements for the degree of Master of Science.

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Acknowledgements

The work for this thesis was carried out with the help of many other people and organizations, and I would like to recognize them for their contributions.

This work was supported financially by the Department of Geography at Indiana University, the Indiana University Office of Sustainability, and the National Science Foundation. I would like to thank the Ostrom Workshop at Indiana University for providing a wide range of resources, including my office space, a remarkable staff, and an engaging academic community.

I am very grateful to my advisor, Tom Evans, for his encouragement and for bringing together many groups of people that I will always appreciate knowing.

My committee members Scott Robeson and Dan Knudsen each offered personal advice and guidance. My three committee members have shaped my education in their own way, and this work reflects their influence.

I am very grateful to everyone involved in the successful field work that was carried out in 2016, namely our colleagues at the Zambia Agriculture Research Institute and at the University of Illinois Urbana-Champaign. I wish great success to the future of this research group and I will be watching their work closely for a long time.

I would like to thank my family – without them I never would have been to Indiana, without them I would not even know what a farmer was.

Thank you to my friends for your support, interest, and encouragement. And thank you Carla, for sharing this and everything else with me.

Abstract

More than three-quarters of households in southern and eastern Africa rely on fuelwood, either charcoal or firewood, as their primary energy source. Fuelwood is a burdensome energy resource, with households spending many hours every week collecting the inefficient fuel.

Collecting and using fuelwood for energy production is closely related to a broader household resource tradeoff system, in which landscape-scale resource availability can limit broader access to resources. Since the 1970s, studies of fuelwood use in Africa have painted the picture of a resource in jeopardy of degrading savanna ecosystems to the point of a massive resource scarcity. Current demographic trends of population growth and urbanization, and climate trends of reduced and more variable rainfall, could be used to predict further declines and uncertainty in the sustainability of widespread fuelwood use.

As millions of Africans continue to use the common resource of the savanna to procure their primary energy source, concerns over the sustainability of the resource and the fuelwood social ecological system (SES) persist. This work provides an overview of the history and current state of resource models that represent the fuelwood SES. Empirical data is used to test assumed relationships between household and landscape level environmental and social factors on household firewood consumption.

Specifically, work for this research investigates fuelwood collection and use in Zambia, first by examining nationwide characteristics of fuelwood collection at a regional level. Then, a subset of the national data is looked at in greater depth, and the subject of firewood consumption is closely investigated. A new method for determining household firewood consumption is presented. Linear regression models of the effect of social and environmental variables on household firewood use are developed and tested.

Results from the national collection survey and the firewood use subsample are used to examine how assessments of the fuelwood SES are characterized and communicated. Scale of analysis and the translation of case study data to aggregate measures of fuelwood use are examined as potential ongoing challenges in accurately depicting the complex interactions between fuelwood users and the resource.

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1 Introduction

Fuelwood, either as firewood or charcoal, are the primary source of energy for 90% of households in areas of Sub-Saharan Africa (SSA), as well as 2.6 billion people worldwide, about 45% of the global population (Twine et al., 2003; Legros et al., 2009). Fuelwoods in southern Africa are obtained through extraction of woody material from forests and savannas and are used daily among households, primarily for cooking, though also in the carrying out of chores such as laundering clothes, heating water for baths, and ironing (Madubansi & Shackleton, 2007). Fuelwood is a burdensome energy source compared to higher energy density alternatives. Household burning of fuelwood is a leading cause of respiratory illness in Africa, contributing to an estimated 400,000 deaths per year in the region (Ezzati et al., 2002). Collection of the resource is highly labor intensive, most often marginalizing potential labor contributions of women and children (Biran et al., 2004). The collective use of fuelwood is also a contributor to global greenhouse gas emissions, including CO_2 emissions from harvesting and burning (1.0-1.2 Gt CO_2 yr^{-1}), and methane and black carbon emissions from incomplete combustion (Bailis et al., 2005; Bond et al., 2013; Bailis et al., 2015).

Total fuelwood consumption in Sub-Saharan Africa is projected to increase as a result of population growth. Population growth is faster in Africa than anywhere else in the world, 2.55% annually between 2010-2015 (UNDP, 2015). Of sub-Saharan Africa's population of 1.186 billion, nearly 60% live as rural subsistence farmers (UNDP, 2015). Rural Africans frequently have no alternative to fuelwood for energy production and urban Africans use fuelwood at a high rate, out of preference or necessity. Africans are migrating to more energy intensive urban areas

(Ahrends et al., 2010). Projections of fuelwood use show that although relative use rates have declined due to urbanization and urban electrification, absolute use has grown and will continue to grow as a result of rural population growth and a widespread urban population with limited access to electricity (Bonjour et al., 2013). To meet the needs of household energy consumption, the region will face increased harvest of woody biomass from forest and savanna ecosystems for human appropriation.

Climate change and the effects on vegetation in the region contribute to uncertainty in assessing the ongoing ecological sustainability of such widespread fuelwood use. On the one hand, increases in global CO_2 concentrations over the last 150 years have facilitated an increase in woody vegetation coverage in African savannas (Bond & Midgley, 2012). At the same time however, precipitation in the region is projected to have greater interannual variability and lower annual totals, which is likely to reduce capacity for woody regrowth in the region moving forward (Sankaran et al., 2005; Stern & Cooper, 2011).

Combined, these processes of climate change and demographic transition could drive degradation and even deforestation of the woodlands and savannas that provide daily energy needs. Such trends pose a threat not only to ecosystem stability, but also to access to a primary household resource that drives livelihood security.

In this thesis, the practices of fuelwood gathering and use by smallholder farmers in Zambia are examined through a lens that has been cast by social ecological systems science. The fuelwood social ecological system (SES) can be defined as the social and environmental dynamics affecting the utilization of fuelwood at local scales, the social responses that emerge to fulfill resource needs and mitigate shortages, and the feedback between such behaviors and a dynamic ecosystem. Given this working definition, the large-scale processes of climate and demographic change only capture the broadest trends of the fuelwood social ecological system, and a clear picture of the un/sustainability of the system needs further examination across regional and local scales.

For this research, socio-economic and environmental variables associated with fuelwood use and consumption at the regional and household levels in Zambia are analyzed. In the process, this thesis will illustrate the longstanding issues in demand side assessments of the fuelwood SES, how these have propagated uncertainty in systematic assessments of sustainability, and how these might be addressed in ongoing models and conceptual understanding of the fuelwood SES.

This thesis uses sample data from rural households that use fuelwood for energy production in Zambia. In this work, firewood using households (not charcoal) make up a majority of the rural population. These households have been under-represented in much of the fuelwood SES literature, compared to charcoal using urban households. In this research, it is argued that the firewood use activities of individual households are inherently variable, but also intimately tied to broader community-level resource characteristics. This research specifically investigates the following research questions:

1) How do fuelwood collection practices vary regionally in Zambia?
2) What social and environmental factors are related to firewood consumption at the household level?
3) How can observed patterns of resource use across local and regional scales improve current understanding of the fuelwood social ecological system?

To answer these questions, this research describes the fuelwood collection practices of farmers among twelve Districts throughout Zambia and focuses on a subsample that examines firewood use among households in a single district, Choma District. In the Choma sample, a novel method of estimating household level firewood use for cooking is used. Results from the reported firewood consumption are then integrated with household survey data and spatial environmental characteristics in a linear regression. In the discussion, the role of household composition in firewood use assessments is considered, as well as the challenges of aggregating household data to predict regional demand patterns, and the potential role of this information in policy and research.

2 Review of related literature

2.1 An history of African fuelwood research

Fuelwood and social-ecological systems

The perceived and potential scarcity of fuelwood as both part of an ecosystem and as a household resource has for many years been a platform for research investigating the presence or influence of a ‘woodfuel crisis’ (Eckholm, 1975; FAO, 1981; Dewees, 1989; Arnold et al., 2006). The ‘woodfuel crisis’ (also known as the ‘fuelwood gap’ or ‘fuelwood crisis’) is a perception that emerged in the 1970s from studies that highlighted the potential for a negative difference between fuelwood supply (ie. above and on-ground woody biomass) and fuelwood demand (ie. the fuelwood consumed by a population of users) in a given area. During the 1970s and through the 1980s this notion of an oncoming (or ongoing) resource crisis became a dominant viewpoint among development economists and others investigating the use of fuelwood in several regions of the world. The ‘crisis’ is grounded in a Malthusian expression of supply and demand. The ‘crisis’ assumed a framework in which resource availability is driven by ecological vegetation dynamics and demand is driven by demographic growth and fuel type/use.

In the 1990s, with more than two decades of ‘fuelwood crisis’ literature in publication, deforestation trends were not occurring at forecasted rates. At the same time, the first wave of development approaches aimed at mitigating the fuelwood crisis were labeled as widespread failures. Soon, the Malthusian population approach to assessing fuelwood use would have to be augmented to fit the real world conditions.

First, fuelwood studies were improved with ecological models that could more accurately represent supply in the savanna ecosystem (Higgins et al., 1999). Using vegetation population ecology theories and landscape ecology science, new approaches to understanding the fuelwood system described a supply that did not respond linearly to disturbances such as harvesting (Desanker & Prentice, 1994; Shackleton et al., 1994). In this new body of work, supply was not assessed as discrete, but as having a complex rate of regeneration dependent on a number of ecological factors including landscape patterns such as patchiness or stem density and climate and weather trends. Savannas began to be described as naturally adaptive complex systems, intimately tied to the disturbance regimes that have shaped them for millennia.

As these ecological theories took shape, social theories were also being developed to explain the seemingly unexplainable behavior of resource users. Once the culprits in 'tragedy of the commons' scenarios, individuals and societies were beginning to be viewed as *part* of these systems, not simply consuming resources but acting and reacting according to conditions. The theoretical relationship between these supply and demand systems, each dynamic and complex, needed a structural undertaking. Social ecological systems science followed.

Recent ecological science narratives of the fuelwood crisis generally go as follows: savannas have existed under disturbance regimes for millennia, certain disturbances (human appropriation) are outpacing historic levels, the ecosystems overall are seeing greater woody productivity (via favorable CO_2 levels), and climate change is driving uncertainty in both supply and demand. Finally, most modern studies conclude that there is not strong enough evidence for widespread concern over the sustainability of the ecosystem, which should remain resilient and stable. This notion of a sustainable fuelwood system providing energy for millions on the African continent however, remains difficult to accept for natural and social sciences alike. This is in part because savannas have been characterized as inherently unstable, susceptible to transition to grassland if disturbance levels are high enough (Higgins et al., 2010). Accepting the system as sustainable also may be perceived as an acceptance of the lifestyle conditions associated with the system.

Modern systems science has laid the foundation for improving assessments of both resource users and environment in the fuelwood SES. But theory has not always been applied efficiently in the collection of data, and empirical measures of complexity (particularly in the social realm) are lacking.

Contemporary models of the fuelwood SES

Despite the accepted complexity inherent in the fuelwood SES, current state-of-the-art fuelwood SES modeling does not diverge far from the supply and demand model that has been employed for decades. The Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) modeling platform was the first widely used comprehensive spatial fuelwood SES model, and many current models are derivatives of the WISDOM model (Drigo et al., 2002; Masera et al., 2006; Masera et al., 2015; Ghilardi et al., 2016). The WISDOM model was designed to delineate 'fuelsheds' based on the spatial distribution of fuelwood use practices and the presence of usable biomass, determined through remote sensing analysis. This work has helped to highlight regions that might be considered fuelwood 'hotspots' where extraction is taking place at a greater rate than regrowth (Bailis et al., 2015). More recently, ecological systems of regrowth in response to harvest or disturbance have further improved the ecological theory underpinning supply, and may soon be integrated into such models (Tredennick & Hanan, 2015; Twine & Holdo, 2016).

Authors of modern spatial fuelwood models point out, however, that there is a serious component of the fuelwood system that has been underemphasized in most models: "A…limitation is that the analysis… does not account for potential behavioural changes among woodfuel users" (Bailis et al., 2015). The same is generally true for a suite of models that treat the fuel-wood SES as a supply and demand relationship between fuelwood users and the forests. Often, demand components of these models simplify human behavior to represent simple consumption within a certain range, regardless of spatially proximate supply scenarios.

Supply measures in the fuelwood SES, have benefited from the continuing improvements in forest monitoring technologies. As higher definition satellite imagery becomes more frequent and computational analysis of massive datasets becomes cheaper, fuelwood supply estimates will be generated with ever greater accuracy and quickness (Hansen et al., 2013). A great deal of the current understanding of widespread woodfuel *demand* however, relies on bridging together disparate datasets and fitting them to the best theories of resource use. As such, delineating the complexities of demand does not benefit from improving technological capacity in the same way that supply measures do. As widespread population projections and high speed communication with remote populations improve, however, there is an opportunity to also improve the way that social data is collected and used to interpret demand. The opportunities and issues therein are in part the subject of this paper.

In this research, the shortcomings of the current literature are investigated. Focus is on how collection and use practices vary, first between regions of Zambia, then among households within the same region. Work for this paper highlights that even among households with relatively similar collection environments and practices there appears to be an inherent variability in the amount of fuelwood (firewood, in this research) used in the cooking process (cooking composes the bulk of household energy use in SSA (Maes & Verbist, 2012)). Furthermore, work for this paper highlights the routine rejection of individual level variability in assessing the demand of the fuelwood SES. This is in part responsible for the longstanding uncertainty in assessments of the sustainability of the SES.

To investigate the claim that uncertainty in fuelwood SES research arises from challenges in reconciling trends across geographic scales fuelwood use must be considered at the local level. In many studies, assessments of regional aggregate fuelwood use rely on extrapolating household responses to basic survey questions (Brouwer & Falcão, 2004; Scheepers et al., 2013; Hoffman et al., 2015). This work investigates the statistical and theoretical relationship between individual households and the aggregate measures of demand that are extrapolated from household data.

2.2 The household and landscape level resource nexus

In rural southern Africa, households sustain their livelihoods most often through small-holder agriculture. For these households, the fuelwood resource is directly tied into the food, energy, water (FEW) nexus (Rasul and Sharma, 2016). The FEW nexus framework suggests that there are tradeoffs in delivering and utilizing the primary resources needed to maintain a basic livelihood, and that the interconnectedness of these resources means that one should not be considered without respect to how it will synergize with the availability and utilization of another. To date, the FEW nexus has been examined primarily on a macro scale, showcasing resource limitations within and between countries (Bazilian et al., 2011; Bizikova et al., 2013). The fuelwood SES, however, presents a new opportunity to examine the role of resource tradeoffs between the meso-and micro scales of resource use and the unique role of fuelwood in resource access and use across scales.

The meso-scale components of the FEW nexus reflect the collective practices of individual households operating within a shared institutional 'landscape'. That is to say, the way that individuals collect and use the resource is tied to, or framed by, the shared norms of the resource users. However, fuelwood use is intimately connected to the characteristics of the physical landscape as well. In Zambia, the landscape mosaic is frequently composed of many small, intermittently fallowed fields dispersed within and across savanna woodlands. These landscape patterns have been shaped in part by generations of agrarian practices and the evolution of cultivating practices in the region. Consider, for example the role of *chitemene*, a bygone agricultural practice typically associated with the Bemba of central Zambia. *Chitemene* is a forest-fallow system of agriculture in which large swaths of forest are cleared and burned, and the resulting ash is incorporated into the soil to add nutrients for cropping. Historically, such forest-fallow systems would occur in cycles over decades or more (Boserup, 1965). However, as the African population grew larger and agrarian practice grew more sedentary, forest fallow systems were no longer a feasible means of agricultural production. *Chitemene* and similar forest-fallow production systems were outpaced by bush-fallow, and bush fallow has mostly made way for plough cultivation today. The effect of the evolution of old agricultural practices however, persists in todays landscape.

As the trend of shortening fallows and more sedentary farming took hold, land has become increasingly fragmented (Haddad et al., 2015). Individual landholdings in Africa typically change readily, with little formality (Peters, 2013). Forests may be chopped or burned, land may be ploughed or fallowed, roads may be built, boreholes may be drilled, forests may grow. All such things happen on timescales each their own, and may or may not favor the influence of the surrounding population. When livelihoods depend on or are defined by access to resources, the local history of land use change and the landscape that inherits its characteristics will shape the daily lives of resource users. In the fuelwood domain, landscape patterns determine how far collectors will have to walk to find wood, what species of wood they may find, whether or not they can use an oxcart or bike to aid their collection, and how fuelwood collection is incorporated into other daily chores.

At the micro scale, in rural sub-Saharan Africa, there is still little substitutability for firewood as the energy resource in people's daily lives. Because fuelwood collection is so time and labor intensive, it is impossible to separate its use from any assessment of livelihood quality. As such, rural households stand to gain the most relative benefit from lower labor inputs and increased efficiency in their energy production. Figure 1 highlights the tendency of individuals sharing a landscape to have similar access to FEW resources, and the role that firewood collection has on a household's overall labor allocation. In this plot, four villages are shown, each composed of a sample of five villagers, represented by polygons inside a triangle. The corners of the polygons are defined by the amount of time that it takes for the individual to reach a common resource when walking on foot. Here, food is represented by the distance to the primary maize field, and water and energy are represented by their locations of collection.

Households tend to have similar access characteristics within a village and this may give insight to landscape level resource access within a village, but there is a great deal of variation (Figure 1). By measuring the cost associated with the energy component of the lives of rural Africans, it may be easier to find opportunities for reducing household labor and access demands and potential improvements in the food, energy and water access domains of individuals.

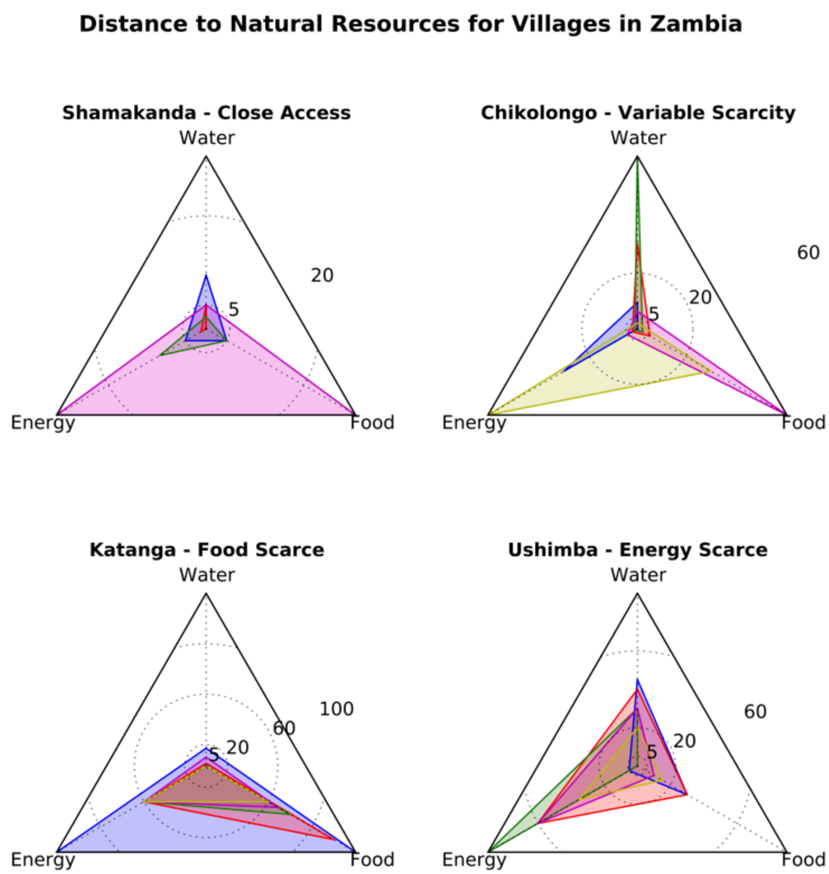

Figure 1 *- Distances to FEW resources, from samples within four different villages; each colored triangle represents reported distance traveled at an individual household; dotted circles represent minutes traveled*

Firewood and charcoal

Understanding the different roles of charcoal and firewood in the lives of the resource user is a first step toward understanding complexity in the fuelwood SES and the role of fuelwood in an overall resource portfolio. Firewood and charcoal are different fuels, their collection and production have intimate and unique feedbacks with the savanna landscape, and their use is deeply tied to cultural differences between the groups of users.

Charcoal in Africa is produced in rural areas through a kiln-fire process that restricts oxygen flow to burning timber, yielding a lighter, more calorie-dense resource than the original wood (Wood & Baldwin, 1985). The process represents a net energy loss due to inherent inefficiency in production, but efficiency is gained in the labor required for transportation and dissemination, as well as at the cooking stove (Antal & Grønli, 2003). After production, the charcoal is transported to highways and urban areas for marketing (Zulu, 2010). Charcoal is produced infrequently by a small number of rural individuals/households for income generation. Production of charcoal is more intensive on above ground biomass than firewood collection, as the charcoaling process requires the clearing of several large trees for the production scale to be economically viable (Chidumayo, 1993). Wood quality is an important input in charcoal production, with higher density wood species being prized for producing higher quality charcoal. Charcoal production in the study region is often regulated, at least in a de jure sense (Zulu & Richardson, 2013). Charcoal production and use has been the primary focus of policy implementation that has been directed at the fuelwood SES (Zulu, 2010).

Firewood collection, on the other hand, is a regular practice for nearly all rural households. Individuals collect and use dry or easily accessible wood that is within walking distance of the household, carrying loads of sticks by hand or, less often, with the aid of a bicycle, ox cart, or vehicle. Wood is selected with consideration to convenience and quality, the latter of which is made up of a combination of species, size and greenness/dryness (Abbot et al., 1997). Firewood collectors are most often women and children (Mahiri & Howorth, 2001; Oparaocha & Dutta, 2011). Often times, firewood collection is carried out among other away-from-domicile chores and so collection locations may be associated with fields or water collection locations (Biran et al., 2004). Groups of women and some children will often collect together. The firewood market is quite limited and the selling of firewood is not considered a viable or consistent form of income like charcoal.

2.3 Household fuelwood reporting – units and methods

Most efforts in quantifying the levels of fuelwood used at the household level or extracted at the ecosystem level focus on charcoal, rather than firewood. This is due to the comparative ease of assessing trends in charcoal use and production at scale as compared to firewood. Charcoal, for instance, is a marketable good that can be tracked by monitoring the visible bags that circulate transportation networks (Kambewa, 2007). High-resolution remote sensing and aerial imagery data are also better suited for monitoring charcoal production than firewood extraction, as the process is more biomass intensive and the production leaves monitorable harvesting and burn scars on the landscape (Chidumayo & Gumbo, 2013; Sedano et al., 2016). Charcoal is also associated with more formal marketing, providing a structured economy that can be tracked through suppliers and purchasers (Kambewa et al., 2007). Charcoal is also primarily an urban fuel source, making participants in the charcoal economy more accessible than their rural, firewood using counterparts. This level of accessibility for researchers has lead to an under-representation in the literature of the impact of firewood as an energy source in fuelwood social-ecological systems.

Measurement standards for fuelwood consumption are inconsistent both within and across spatial scales. Aggregate continental and regional studies of consumption, such as those carried out by the FAO, tend to use cubic meters as the unit of measurement of fuelwood consumption (FAO, 2003). These volumetric measurements are compatible with satellite image-derived aboveground biomass measurements that are used to assess supply across broad regions. Household level measurements however tend to record consumption in units of mass, typically kilograms. The prevalence of units in mass at the household level is likely due to the relative ease of mass measurement compared to volume when the resource is made up of small sticks and logs. This complicates the aggregation of household level surveys to a regional metric, as the mass-volume relationship of wood pieces is dependent on fuelwood species and water content.

Even among household level mass-based consumption reporting there is great variability in the units and methods used by researchers to describe consumption. This makes synthesis and comparison of multiple studies cumbersome. Peer-reviewed fuelwood (specifically firewood) consumption case studies in Africa are surprisingly few given the high volume of theoretical work and regional assessments of the topic.

Appendix A synthesizes consumption data from fourteen peer-reviewed journal articles quantifying firewood consumption from direct household measurements in southern and eastern Africa. Articles in this literature review represent a comprehensive view of peer reviewed studies undertaken to determine firewood use at the household level in SSA over the last 20 years. Due to the nature of breadth-of-search literature reviews like this, many of the objectives and measured elements of the case studies differ, and the consumption metrics used in each study may reflect this.

From the 'consumption reported' column of Appendix A, it is apparent that there is no standard time or mass unit for reporting firewood use. In the literature review, volume measurements have been excluded, because of the difficulty in accurately converting small volumetric measurements to weight, particularly across different regions where variability in plant species will make for different wood densities. From the reported consumption in these studies, simple unit conversions were made where possible to present the data in kilograms of firewood per capita per year. Kg $cap^{-1}year^{-1}$ is the unit that had the most direct conversion from most of the reported consumption observations, and is the unit that has been used for similar literature reviews (Johnson & Bryden, 2012).

The kg cap^{-1}year^{-1} firewood use from each publication is plotted, along with the year of the publication in Figure 2. For articles with two distinct samples, both samples are included as separate points in the figure. Many studies have multiple small samples; often these studies also include mean firewood use across samples, which became the measure included in Figure 2.

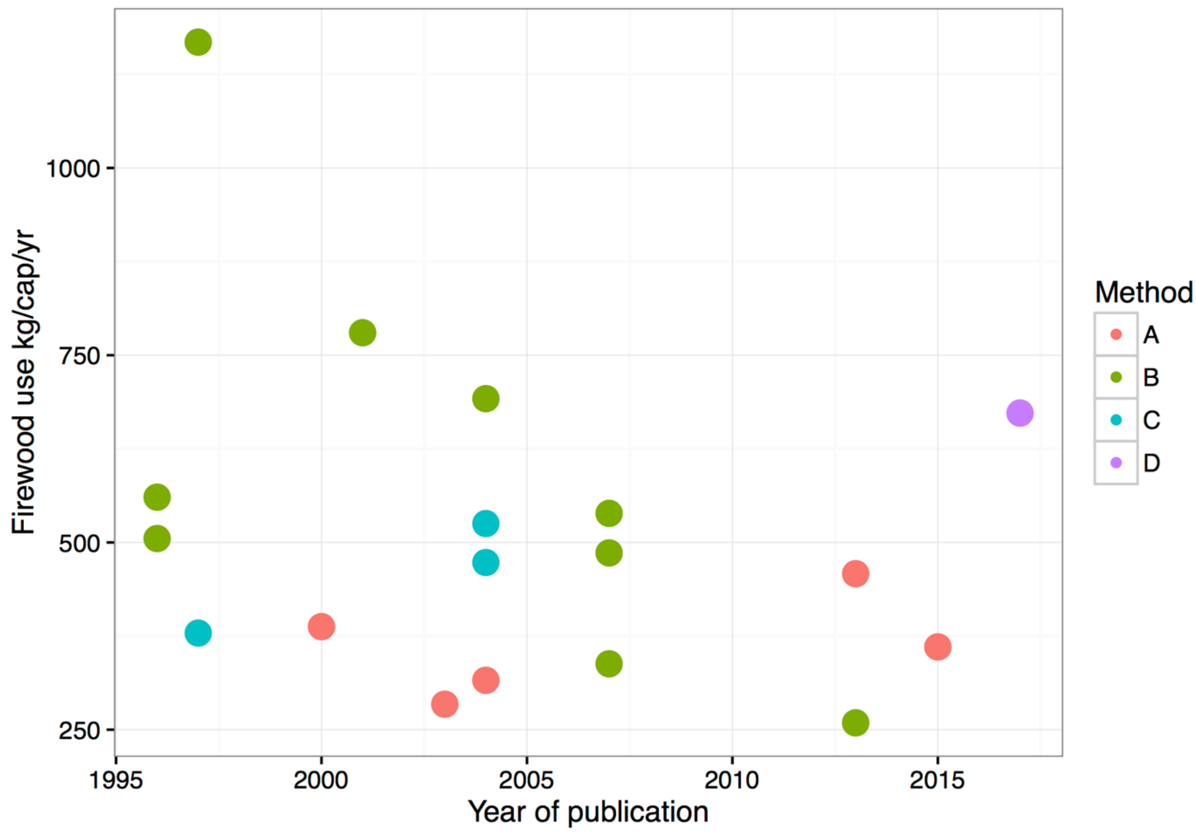

Figure 2 *– Meta-analysis of per capita firewood use/year and year of publication; Methods - A: proxy, B: self-appraisal, C: first-hand, D: firewood selection exercise*

Along with date of publication and reported firewood consumption, Figure 2 provides an overview of the types of methods used to produce the reported consumption measure. The literature review reveals that studies typically use one of three standard methods to determine firewood consumption at the household level: proxy, self-appraisal, and first-hand measuring.

Through the proxy method, consumption is estimated based on household responses survey questions. Such questions are typically short, and easy to include in a household survey that can be administered quickly to a large sample. The proxy method is the most common method for large-scale and national surveys (KFS, 2013). Common questions may include: ‘how large are the headloads collected at this household’ and ‘how many headloads are collect per week’? Regional aggregate measures also use proxies to make estimates of fuelwood use (Bailis et al., 2015).

With the self-appraisal method, researchers ask household members to pull firewood from their reserves equal to the amount of wood that they would use for cooking in a day. The wood is then weighed on site using a balance and recorded as the daily consumption rate. In the first-hand technique, the researcher leaves a bundle of firewood of known weight at the household and requests that the household only use wood from the given pile for cooking over the next 24 hours. At the end of the 24 hours the researchers return and weigh the amount of firewood left in the bundle; the difference between the original weight and the weight 24 hours later is the amount of fuelwood consumed at the household for the day.

The proxy method has obvious limitations, which this paper is attempting to highlight. The self-appraisal method fails to control for greenness of wood (households often collect wood and store it for a time before it is ready for use). And the first-hand method is time and labor intensive, while it also does not account for species preferences of the cook.

Though the work here introduces yet another reporting methodology (Method D in Figure 2, covered in detail in Chapter 3) and reporting units, the collection and synthesis of the various reporting units must be done for the sake of future research. Ideally, production of an intensive literature search should yield data that can be easily applied to a longitudinal studies of demand in a region. Consistent units in publications would be ideal, but is far from reality, thus, direct measurements should be reported in units that are easy to convert.

3 Study area, sampling and methods

The primary data for this study consists of survey responses from a sample of farmers within Zambia. The sample includes: a nation-wide sample of smallholder farmers throughout Zambia and a within-district subsample of household firewood use in Choma District of Southern Province.

3.1 Study area

Zambia's energy profile

Zambia is a landlocked semi-arid country in central southern Africa. While 39.51% of the country's population of 13.01 million are urban dwellers (CSO, 2010), the country's rural population live on meager resources. The primary source of livelihood for much of the country's rural population is agricultural subsistence. The country has a population density of about 17.4 people per km^2, though this can be much lower in rural districts, in which population density is typically in the range of 7-10 people per km^2 (CSO, 2010).

Surveys for the nation-wide analysis were carried out among 12 districts; two districts were selected from each of six provinces in Zambia (Figure 3) representing a gradient of precipitation based agro-ecological zones.

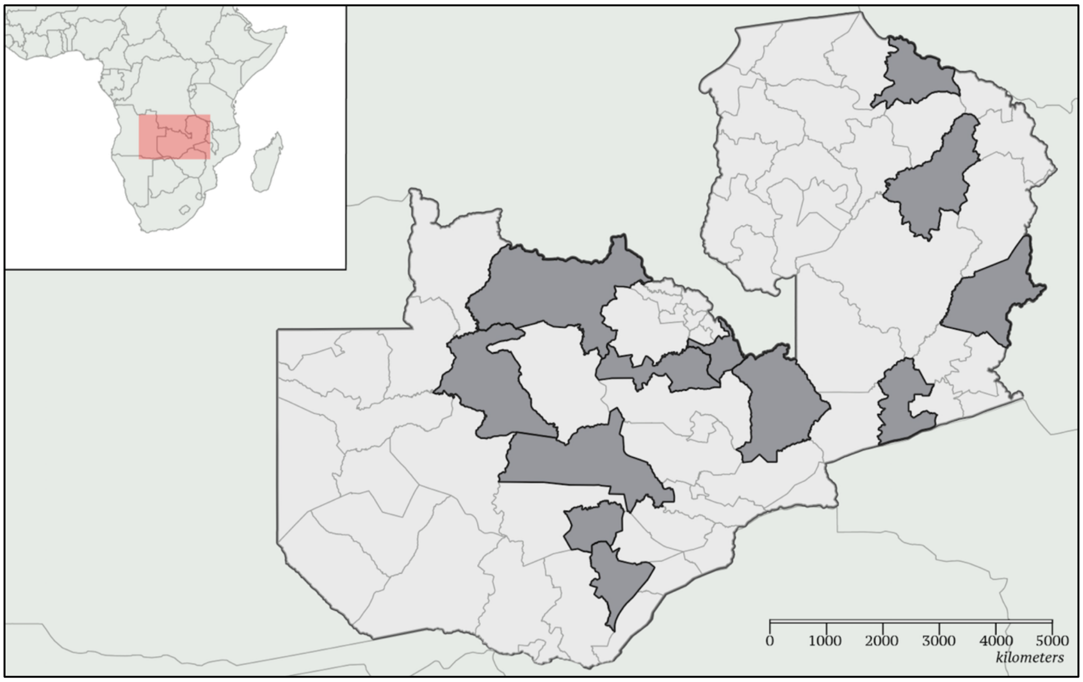

Figure 3 *- Map of Zambia (main) and its location within southern Africa (inset); the twelve districts sampled for the analysis are highlighted in dark gray*

Throughout the rural parts of the country, economic opportunities are limited, and families and communities are often susceptible to resource scarcity in the food, energy and water domains. The rural poor in Zambia use firewood as their primary energy source at a rate that is similar if not slightly higher than the southern African region overall (Table 1). Relatively few households have access to grid power, which has been unreliable in recent years due to inefficiencies in the generating power of the country's largest infrastructure project and primary power generator, the Kariba Dam.

Access to alternative fuel markets is also lacking. Though solar power generation is being adopted at high rates among rural households, most panels are still too expensive for a household to afford anything more than 100W (most are just large enough to power a small radio or cell phone). Recently, proposals have been approved by the World Bank to develop a large scale (55 megawatt peak) solar plant in the country, which will help to mitigate some of the power troubles that have stemmed from the failures of the Kariba dam (WB Project ID: P157943). Distribution of electric power to the rural population, however, is almost nil. Access to household solar power is increasing, and cheaper, more efficient home panels are likely to provide some relief from energy poverty in the coming decades (Pillot et al., 2017).

Table 1 | *Household access to electricity and primary cooking fuel from a survey conducted among 18,052 households in Zambia, 2014. Results indicate that rural cooking fuel is often (97.6%) forest derived and that charcoal and electricity are far more common in urban areas. (CSO Zambia, 2014)*

	Urban	***Rural***	***Total***
Access to Electricity			
Yes	61.5	3.8	27.9
No	38.5	96.0	72.0
Primary Cooking Fuel			
Electricity	26.9	1.8	12.3
Charcoal	67.2	15.6	37.1
Wood	5.8	82.0	50.2
Straw/shrubs/grass	0.0	0.3	0.2
Animal dung	0.0	0.2	0.1
No food cooked	0.0	0.1	0.1

There is some evidence that charcoal production has increased in Zambia over the last 30 years, as demands for charcoal increase have increased growing urban populations (CSO, 2010). Zambia has attempted to regulate the charcoal trade by making commercial production on non-private land illegal without permitted approval from the Forestry Department (Government of Zambia, The Forests Act of 2015). Surveys and field experience from this research, however, suggest that production is taking place a higher rate than permits would allow and that the rule has been more effective at eliciting bribes from producers than in preventing production. There is a fundamental tension in protecting forest resources versus enabling smallholders access to a source of energy (fuelwood) critical for cooking.

Firewood consumption subsample

Within the 12 district sample a single district in Southern Province, Choma District, was administered a more in-depth survey to delineate household level firewood use. Choma district[1], is 7,380 km^2 and has a population of 247,860 (CSO, 2010). The district population in 2000 was 204,898, giving a population growth rate of about 1.9 percent for the decade.

Just west of the geographic center of Choma district is the market town of Choma. The seat of Southern Province, Choma town had a 2010 population of approximately 62,335, about one quarter of the total district population. There are two major paved roads in Choma district: the Lusaka-Livingstone road running from the south-western tourist-town of Livingstone at the Zimbabwean border, northeast to the country capital of Lusaka, and a Zambian road that runs northwest to southeast. The intersection of these roads, and the trade that runs along the road between Livingstone and Lusaka, has made Choma town a bustling hub of commerce in the otherwise remote and sparsely populated district.

Outside of Choma town, the rural inhabitants of the district are mostly subsistence farmers. Here, smallholder farmers maintain their livelihoods by collecting and utilizing basic resources. Food is, by volume, primarily maize, water is extracted from boreholes or wells and energy comes from burning firewood.

The rural landscape is a mosaic of agricultural fields interspersed among the 'dry miombo' woodland savanna. The miombo woodlands are characterized by trees in the *Brachystegia* and *Julbernardia* families, with a single primary canopy at around 5 meters, and a relatively low (20-40%) canopy cover in even the densest areas (Chidumayo, 1997).

[1] In 2012, Choma district was split into Choma and Pemba districts. In 2010, the year of the most recent nationwide census, Choma and Pemba were a single district. Because all demographic measurements in this study are based on the 2010 census, the study area is referred to as 'Choma' or 'Choma district'.

3.2 Household Surveys

The country-wide survey for this research took place over 8 weeks between June and July, 2016. The survey was carried out among 1198 households across the 12 districts. The long-form survey in which these households participated included questions regarding household socioeconomic and demographic traits, as well as agricultural and resource use practices and perceptions. During the survey, households were asked about their firewood collection practices and the availability of firewood resources, but consumption measures were not taken directly (Appendix B).

Questions in the survey were developed to delineate the time and labor inputs involved in collecting firewood, the conditions of the environment in which the household collects, and attributes of the collectors. Households were also asked about the influence of government regulations and in/formal rules on collecting. The fuelwood component of the survey was designed to take about 20 minutes, and questions were designed to be easily mapped to variables, either alone or as part of an index.

The extended surveys in the Choma subset were carried out among rural smallholders during a three-week period in July 2016. During this time, 181 households participated in a short firewood consumption reporting exercise (Appendix B). Of the 181 households, 140 were also part of the 12 district sample and participated in the long-form household agricultural survey; the 140 household sample are used as the ‘Choma subsample’ for this research (Figure 4). The 41 households that participated in the firewood consumption exercise but did not participate in the longer survey were excluded from any analysis.

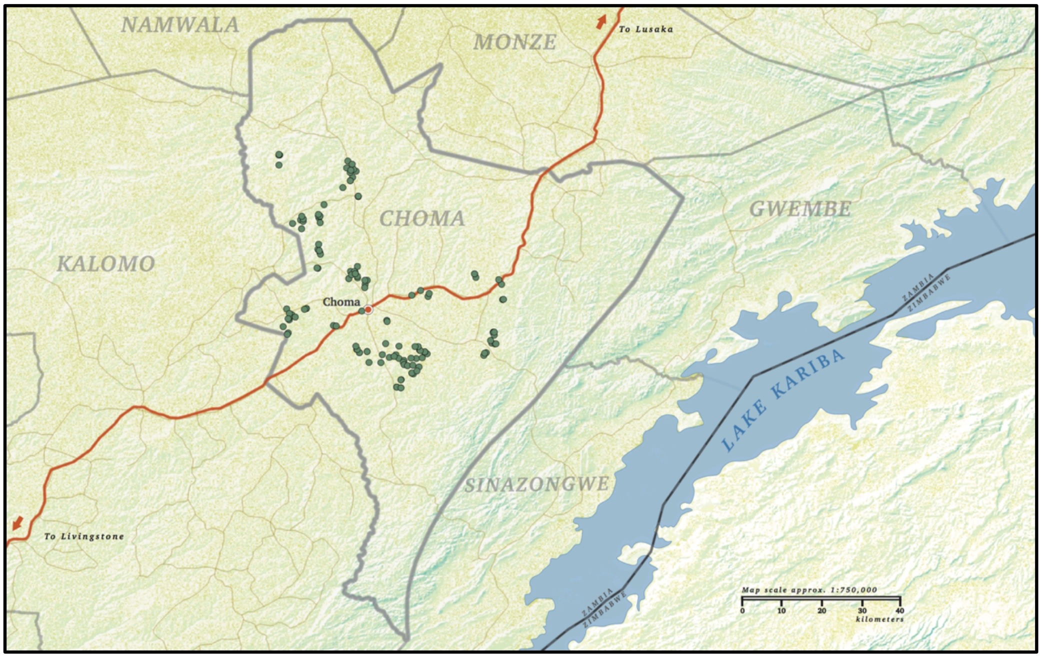

Figure 4 *- Map of Choma District and households surveyed for the case study; household locations have been anonymized and dithered, with the approximate distribution represented by green circles*

Reporting household fuelwood consumption

Following the firewood household survey, participants in Choma district were asked to complete a firewood consumption reporting exercise to delineate the amount of firewood the household uses in daily cooking activities. The firewood reporting exercise was designed to minimize the known biases that occur in reported fuelwood consumption surveys. The exercise is designed to be repeatable, and to be more time and labor efficient than the current most common methods of determining fuelwood consumption.

The selection exercise should provide more detailed data than methods that rely on proxy indicators. Using the method reported in this paper may also open up opportunities to studying the relationship between perceptions of volumes and weights, as well as the capacity of cooks to choose species that match their reported preferences.

For the firewood consumption reporting exercise, household cooks were presented with a bundle of wood composed of 30 pieces, similar in appearance to that of a common wood bundle that is typically collected in a headload (Figure 5). Sticks in the bundle were from a variety of species, meant to reflect the composition of woodlands in nearby forests. Wood for the exercise was collected from dried stocks at the Mochipapa Research Station, a governmental research facility centrally located in the survey sampling framework. A panel of forestry experts at Mochipapa reached agreement on the species of each of the wood pieces included in the exercise. Each piece was then labeled for identification during the exercise. The pieces were weighed to a precision of 10g, measured in millimeters for length and for circumference at the butt, middle and tip (for producing volume measures as outlined in Harmon & Sexton, 1996). Weight and circumference measures were taken daily to ensure the ongoing integrity of each piece of wood, when weights differed by more than 20g from the original weight (due to breakage or wear) the piece was retired and a replacement was made in the bundle.

Figure 5 *- Image of a typical head/shoulder load of firewood (left); a 'three-stone' stove, the most common implementation for cooking (right)*

***Figure 6** – A woman participating in the firewood selection exercise*

Primary cooks from each sampled household were asked to participate in the survey as these participants are likely to be more accurate reporters of consumption than those who do not cook. For the exercise, household cooks were presented with the bundle of labeled firewood pieces (Figure 6). Each participant was asked to select from the bunch those wood pieces that would be 'enough, but not more than enough' to cook a given meal: morning, midday or evening. After selections were made for a meal, an enumerator recorded the selected pieces and wood pieces were returned to the original pile and the survey continued until all meals at the household were accounted for. From the recorded responses, pieces could be matched by their identifying label with the weight and character of the wood and a sum of the weights of each selected piece made up the total weight used for each meal and each day at the household. Volume was calculated in the same way.

Several bundles were used during the sample collection period, the average weight of the wood pieces was 537 grams, the average weight of the entire bundle was 13.5kg, the range of potential daily reporting of household firewood use was approximately 0-40.5kg (13.5kg for each of 3 meals).

3.3 Models of firewood collection and use

District level models of variation in collection practices

In undertaking initial statistical analysis of the sample, the household responses from each district in the country wide analysis were used as subsets of the national sample to test for differences in collection variables across the country. The districts (n = 12) made for a categorical variable that could be used to examine how collection practices vary spatially, by comparing within sample variation to across sample variation. There are two common options for comparing within sample variation to across sample variation of a variable: 1.) a one-way ANOVA test or 2.) a linear regression using a single categorical (dummy) independent variable. The two techniques provide the same information (Harrell, 2015), so linear regression technique ultimately chosen because of its ease of implementation and interpretability.

Three collection variables were tested as dependent using 11 districts as independent variables for each regression and omitting Choma district, making it the intercept for the regressions. The variables chosen were: distance to collection location (in minutes), total time for each collection trip (in minutes) and trips taken for firewood collection per week. These variables, derived directly from questions asked in the household survey, are emblematic of those that would typically be used for developing proxy measures of firewood consumption at the household level (see Appendix A for examples).

Models that test for difference in means across samples require homoscedasticity (or consistency in the variances) across the samples. The Breusch–Pagan test was used to test the variables for homoscedasticity (Breusch and Pagan, 1979). Distance to collection location and trips per week showed that homoscedasticity was present. Total collection time per trip however failed to pass the test for homoscedasticity (Breusch–Pagan test; $p < .000$). This may be attributable to the presence of some distance outliers in a few districts. To generate a more normal distribution for the total trip collection time, a logarithmic transformation was performed on the response data, producing homoscedasticity across the samples. Some interpretability is lost by using the logarithmic transformation.

Household level models of firewood use

Several studies have investigated the influence of household and local environmental variables on the rates of fuelwood consumption at the household, and have as such highlighted a consistent set of variables that may explain some variance in use rates (Palmer and MacGregor, 2009; Bandyopadhyay et al., 2011). Using the reported firewood consumption measures taken at each household in the Choma case study, a multivariate ordinary least squares regression model for firewood consumption was developed. This model uses independent variables associated with firewood collection and use to determine what amount of variability in reported firewood use can be accounted for using standard survey techniques and remotely sensed environmental data.

Models presented here use reported firewood consumption (in kg/day as reported by the selection exercise in the Choma subsample) as the dependent variable. The reported daily firewood use results made for a continuous, mostly normally distributed dependent variable. Both household-level (the reported value) and per-capita-level (the reported value divided by reported household size) fuelwood consumption were tested as dependent variables.

Explanatory variables at the household level are listed in Table 2. These variables are meant to represent the most common variables associated with fuelwood consumption that have made up the literature over the last several decades (see work by Hosier, 1988 for an early and extensive explanation of variables expected to influence fuelwood consumption). The regression model itself was built to reflect the notion that each of the chosen dependent variables is expected to influence the amount of firewood consumed at the household. Independent variables were tested for collinearity (Figure 7). The re

All were derived from the household-level survey data except the variables for percent forest cover and difficulty in collecting.

Table 2 | Regression independent variables and their expected relationship with household firewood use

Independent Variable	Expected coefficient relationship	Description
Household Size	+	Households with more people require more food and more fuelwood to meet this need.
Collection trips per week	+	Collection trips per week has been a reliable indicator for consumption rates in firewood use (Pattanayak & Sills, 2004). When households collect firewood for cooking in Choma, the most common practice is to collect by hand. Knowing the number of collection trips per week at a household can set a range of expected weight or volume used at the household. If households are bringing 2 or 3 headloads of wood home per week, they are likely to be using firewood a higher rate than a household that collects 1 headload per week, assuming a small variance in the weight of a headload.
Distance to firewood collection location (minutes)	-	Distance to firewood has been used for years a measure of availability (Hosier, 1988). Simple economic theory suggests that greater labor costs (time and effort) will encourage households to be more energy efficient.
Household income (Zambian Kwacha)	+	Income has been theorized to correlate positively with energy use across populations (evidence for this theory may not hold up well within populations). In general, this theory follows an energy-ladder type hypothesis, in which as income increases, households may shift fuel sources to more energy dense (and more expensive) alternatives. In this a scenario, as income increases, energy becomes both more abundant (with fuel density) and cheaper (labor per calories), which drives up energy consumption. An alternative view is that as income increases, consumption overall increases. In models reported here, the income variable is tested in a population that does not fuel-switch.
Collection by Hand (binary)	-	If a household collects strictly by hand (that is, without the use of an ox cart, bicycle or other vehicle) one can expect them to have a higher labor cost for collection and to use less fuelwood.
Percent forest cover	+	See subsection below
Difficulty in collecting	-	See subsection below

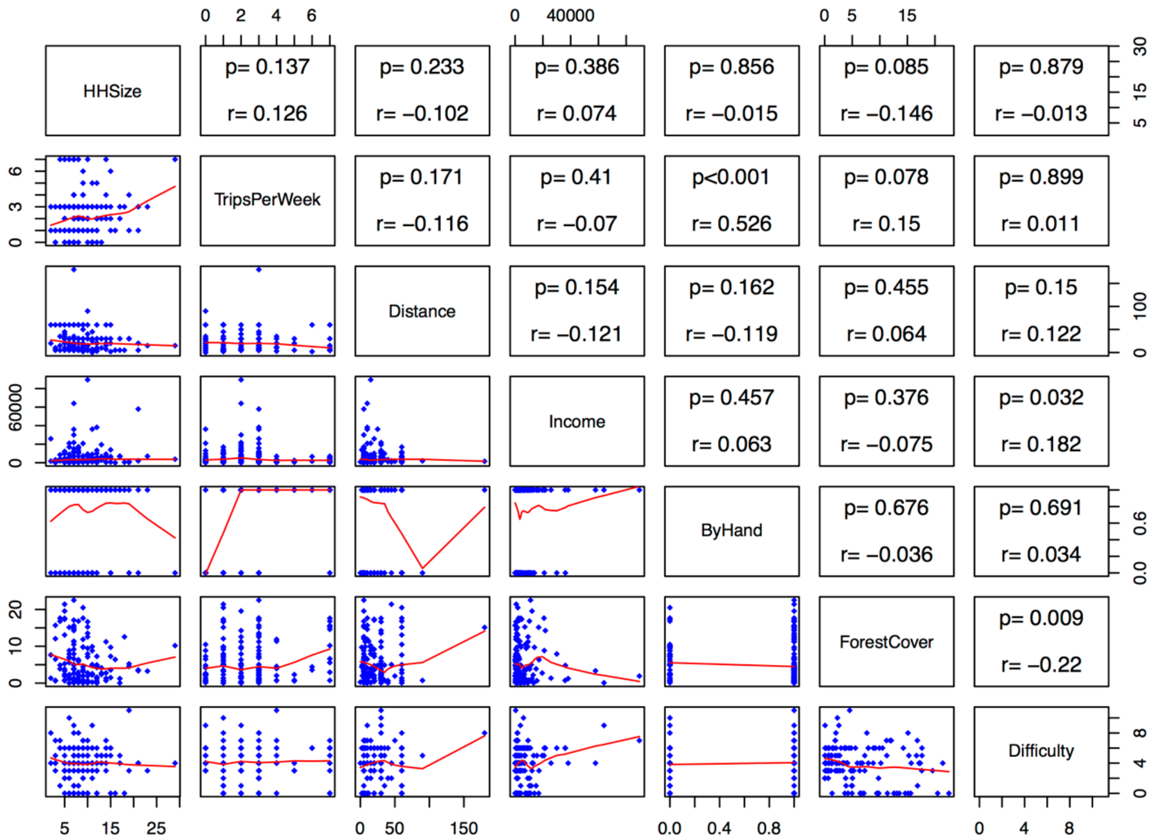

__Figure 7__ - Correlations among household attributes for the Choma firewood consumption regression; red lines are locally weighted regressions

Determining percent forest cover for the model

Included in the regression is a land cover dataset that acts as a proxy for potential resource availability around the household. The land cover dataset was derived from Landsat 8 imagery from February 2016, in which each pixel (30m resolution) was classified as forest, savanna, agriculture, water or urban. The land cover classification was carried out according to methods outlined in Sweeney et al., 2015. For this study, the forest land cover class represents pixels in which woody canopy cover makes up more than 40% of the pixel area in each pixel.

For each household a sum of forest pixels was calculated from pixels within a window of 150x150 pixels (4.5km by 4.5km window) around the household; this sum was then divided by the total number of pixels in the window to yield the portion of forest land cover within a $4.5km^2$ window of each household. $4.5km^2$ (about 2.25km from the household in directions aligned to the orientation of the pixel grid) was chosen because it represented an area that could reasonably be covered during most collection practices (households in the Choma subset had a mean distance to collection of about 24 minutes).

Index of Collection Difficulty

The ‘collection difficulty index’ included in the model is derived from a series of Likert scale responses to questions about the significance of forest conditions in contributing to difficulty in the task of collecting fuelwood. The index is a simple sum of respondent impact on firewood collection location from: fires, forest clearing for agriculture, forest clearing for charcoal production, new restrictions to access in collection locations, increased demand from other firewood collectors on household collection location and a catch-all ‘other’ category. Responses were ordered from 0 (‘not significant) to 2 (‘very significant’) for each possible difficulty. In using the index, a higher number represents a higher level of impact on the collection area.

4 Results

4.1 Variability in firewood use within Choma District

Choma district has distinct fuelwood consumption and collection attributes among districts in the 12 district sample. Choma has the second lowest rate of charcoal use among all districts, with only 22.28% of respondents from the district sample (n=263) using charcoal for cooking over the last six months. Choma district respondents also spent the second least amount of time collecting on average, reported the shortest average walking distance to their fuelwood collection location and reported the second highest average number of trips per week among the districts.

Together, these attributes conjure an image of a district in which accessibility to firewood is not an outsized challenge compared to other districts. Very few Choma respondents report distance to the resource as being an obstacle in firewood collection, with many reporting that density of woodlands and quality of wood are their primary obstacles. This seemingly adequate access to the resource may be an indication that charcoal use and production is not necessarily a priority for Choma farmers.

Choma respondents also have low levels of firewood and charcoal purchasing, but are among the highest in solar panel ownership. Reported median landholdings in Choma (along with nearby Namwala) were the highest among all districts, and reported median income is squarely in the middle of the 12 district sample.

All households in the Choma case study sample (n=140) used firewood as their primary daily fuelwood, although 17 households (12%) reported using charcoal at some point during the seven days prior to the survey. Households that cited using charcoal during the last 7 days did not report a significantly different amount of firewood used for cooking (mean =p=0.549, two-sided t-test), and none cited charcoal as a primary fuel source.

As expected, reported firewood use is highly variable among households in the Choma case-study sample. Reported household firewood use ranged from 6.4-32.0 kg/day with a mean of 14.2 kg/day and a variance of 16.7 kg/day (Figure 10). For morning, midday, and evening meals the mean of reported firewood used was 3.5 kg, 5.6 kg and 5.1 kg, respectively.

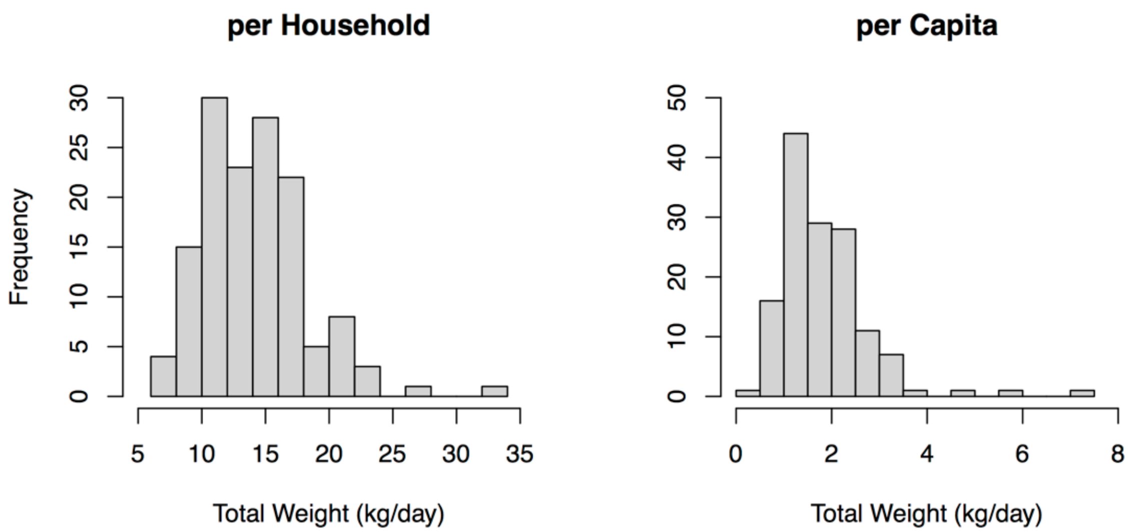

Figure 8 *- Histograms of daily reported firewood consumption for the household (left) and per capita (right)*

All analysis of fuelwood in this paper was conducted using units of mass (kilograms). However, the consumption reporting methodology gave the option of using volume. Ultimately mass was chosen because it aligns with the majority of case-study work on fuelwood consumption. The relationship between mass and volume in responses, however, was highly linear, with a correlation coefficient of .98 and an R^2 of .96 (Figure 11).

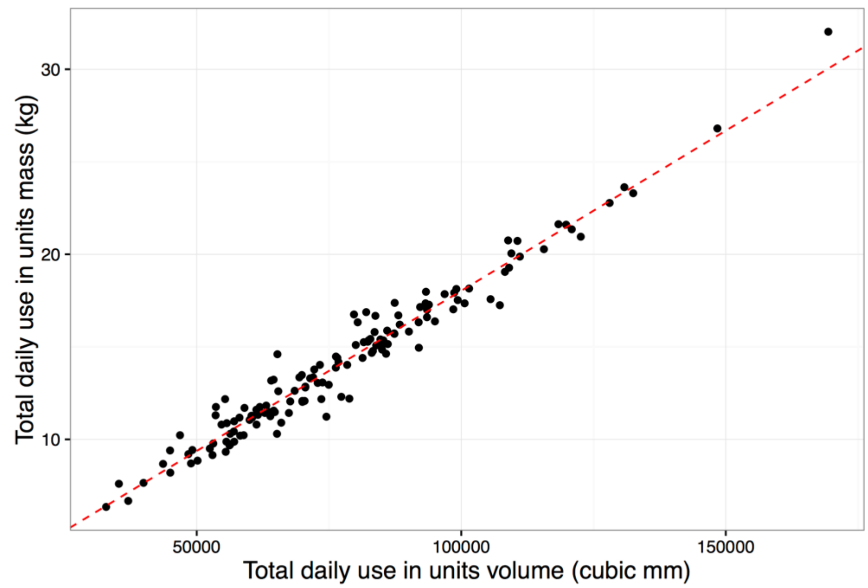

Figure 9- *Volume and mass correlation for the firewood selection reporting exercise*

In the Choma sample, 36 farmers stated that members of their community were active in charcoal making, and 4 responding households reported producing charcoal themselves at some point during the previous 12 months. Though the presence of a charcoal producer did not influence reported firewood use, those households that reported charcoal producers in the community also report significantly greater perceived difficulty in collecting (mean = 4.9 on the difficulty index) than those who did not report charcoal producers (mean = 3.6; p = 0.005, one-sided t-test).

Collecting by hand was the most common practice for all households, though 33 cite using an oxcart for collection as well. There is some evidence that those that collect by hand use more firewood (mean = 13.2 kg) than those that sometimes use an oxcart (mean = 14.6 kg; p = 0.046, two-sided t-test).

All but 15 of the 140 respondents in Choma district reported that firewood is used at the household for additional chores (heating water for baths, heating water for laundry, space heating, ironing, and/or other). Heating water for baths was an almost ubiquitous daily task (115 households heat water for baths every day). Although the practice of heating baths is likely less common during the hotter months, it is no doubt a contributor household forest resource use annually. There is little evidence of correlation between using firewood for additional household activities and the total weight used for cooking (Pearson's r = 0.074). This goes against intuition, or the thinking that those households with greater ease of access would use more overall (for both miscellaneous chores and cooking specifically). However, because the auxiliary use index is a simple *count* of activities, it does not adequately represent how much energy a household would need to perform each task (e.g. the temperature to which water is heated or the length of a bath).

Descriptive statistics of variables for the household linear regression models can be found in Table 4 below. All continuous independent variables appear to be normally distributed except for income, which is positively skewed. Normally, positively skewed distributions benefit from logarithmic transformation to provide a more normal distribution; however, in this case transforming the income distribution logarithmically did not have much influence on the significance of the income variable, or the overall explanatory power of the model. As such, income was left as reported by households to allow for greater interpretability of the coefficient.

***Table 3** | Descriptive statistics for household regression variables in Choma district*

Statistic	N	Mean	St. Dev.	Min	Max
Firewood consumption (kg/Household	140	14.16	4.09	6.350	32.025
Household size	140	9.09	4.33	2	29
Times firewood collected per week	140	2.41	1.82	0	7
Distance to firewood (minutes)	140	23.97	22.46	0	180
Income (Zambian Kwacha, annually)	140	6,903.64	12,104.48	0	89,500
Forest land cover (percent in 4.5km window)	140	5.83	5.73	0.00	22.53
Collects by hand	140	0.69	0.46	0	1
Difficulty in collecting (index)	140	3.96	2.36	0	11
Clearing of forest for agricultural lands	140	0.26	0.57	0	2
Clearing of forest for charcoal production	140	0.31	0.60	0	2

New restrictions to access protected areas	140	0.39	0.76	0	2
Increased demand on firewood collection area	140	1.64	0.74	0	2
Fires	140	0.96	0.78	0	2
Other	140	0.40	0.61	0	2

Regression Results

Households in Choma represent a range of fuelwood consumption levels, suggesting that fuelwood consumption may be unique to household attributes. The variables chosen for the household model reflect many of the previously hypothesized social and environmental influences on fuelwood use, and the results suggest that some of the presumed relationships hold true in the Choma subsample (Table 5). Household size and collection trips per week both have a significant influence on household firewood consumption; both have positive coefficients as expected.

Forest land cover percent showed a significant negative coefficient. This relationship defied our expectations, and the implications for this relationship are discussed in detail in Chapter 5. Collection difficulty showed a significant positive coefficient, suggesting perhaps that difficulty increases with the amount of firewood needed, contrary to the expectation that difficulty in collecting would reduce consumption. By hand collection was not a significant variable in the regression despite being significant in a t-test of mean firewood consumption between by-hand collectors and technology-using collectors, this merits further investigation.

Overall, more variation in the per capita dependent variable was explained than the household level variable, which may be a function of the relationship between household size and resource use efficiency. This finding suggests the importance of considering household size when evaluating the impacts of population on widespread fuelwood consumption.

The residuals of the regression were examined and had a fairly even distribution, the residuals were also mapped, though they showed no apparent spatial pattern.

Table 4 | Household and per capita firewood consumption linear regression results

	Dependent variable: reported firewood use	
	per Household	per Capita
	(1)	(2)
Household Size	0.249	-0.147
	p = 0.001***	p = 0.000***
Times firewood collected per week	0.442	0.064
	p = 0.033**	p = 0.105
Distance to firewood (minutes)	0.011	0.001
	p = 0.413	p = 0.628
Income (Zambian Kwacha, annually)	0.00003	0.00001
	p = 0.326	p = 0.280
Forest land cover (percent in 4.5km)	-0.222	-0.021
	p = 0.0002***	p = 0.049**
Collects by hand (1 = yes)	0.381	-0.113
	p = 0.628	p = 0.451
Difficulty in collecting	0.262	0.055
	p = 0.054*	p = 0.036**
Constant	10.374	2.945
	p = 0.000***	p = 0.000***
Observations	140	140
R^2	0.289	0.486
Adjusted R^2	0.251	0.459
Residual Std. Error (df = 132)	3.542	0.679
F Statistic (df = 7; 132)	7.651***	17.861***
Note:		*p<0.1; **p<0.05; ***p<0.01

4.2 Household fuelwood consumption

The stark difference in the explanatory power (R^2) of the household and per capita models was worth investigating more closely. The results from the per capita regression suggest that there is a strong relationship between household size and *per capita* fuelwood use. Following this insight, a functional relationship was developed to represent firewood-use efficiency with gains in household size in the Choma sample (Figure 12). The best fit for this equation is a negative exponential (Equation 1), which suggests that gains in household firewood use efficiency are high for additional household members at a low household size, and efficiency decreases as household size increases. The slope of the line is interpreted to represent the *gain* in firewood use efficiency ($\frac{\partial kgcap^{-1}}{\partial HHSize}$). So while households of greater sizes have lower additional total firewood consumption for each additional person (marginal fuelwood consumption), households of smaller size will see a greater change in per person efficiency with each additional person.

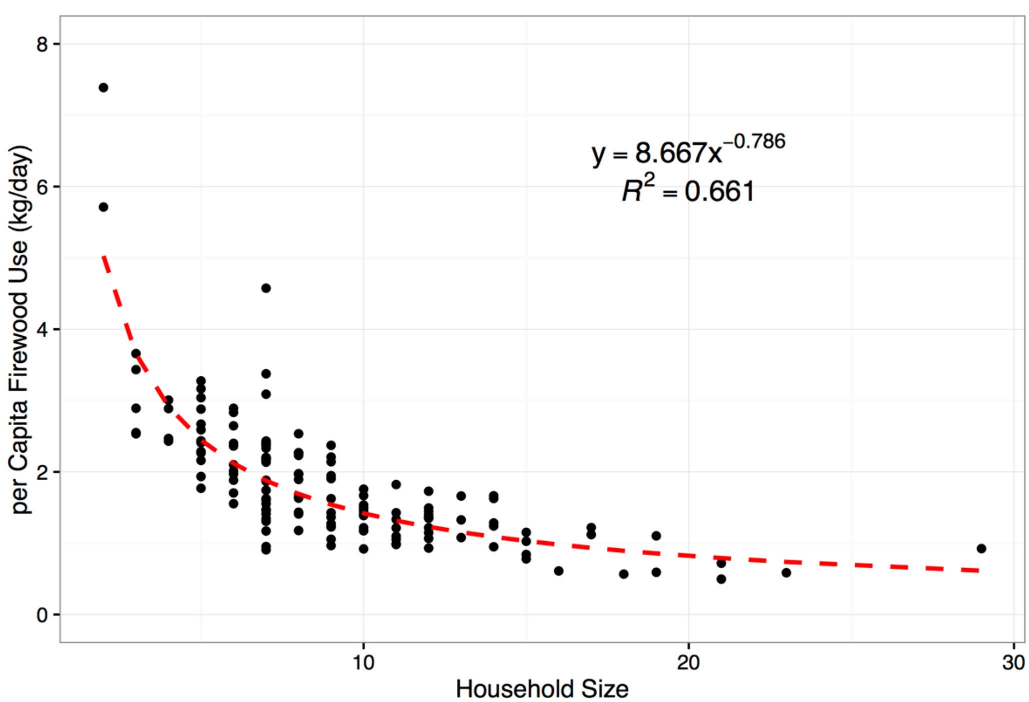

Figure 10 *- Household size and per capita firewood use in the Choma subsample*

$$C_{FW} = 8.667 \cdot HHsize^{-0.786} \quad (1)$$

This relationship is intuitive, and economies of scale in household consumption of resources have been highlighted in a broad sense in the literature (Nelson, 1988). It is likely that this relationship fits the Choma sample so well because of the presence of larger sized households in Choma, which may not be as common in other districts (Figure 13).

The large average household size in Choma may facilitate the ubiquitous use of firewood in the area as well. Choma households use firewood as their primary energy source more than any district (save Lundazi), but also have a fairly positive outlook on their firewood accessibility. With such large household sizes and easy resource access, the incentives for charcoal production and use may not be as obvious or dire as they are in other districts.

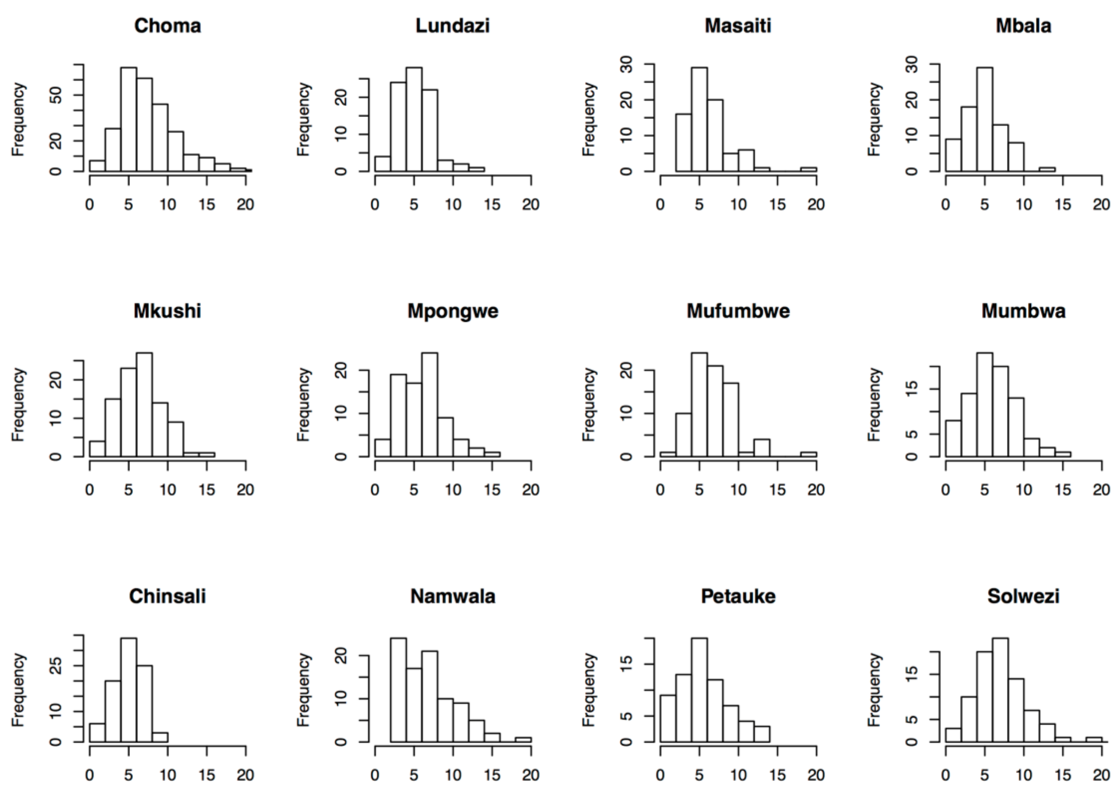

Figure 11 *- Household size distributions for each of the 12 surveyed districts*

Calculating aggregate demand

Chapter 2 highlighted the history of uncertainty in measures of supply and demand when addressing the fuelwood social ecological system. While empirical measures for this research don't have the complete information necessary for a comprehensive demand estimate of Choma district, the results can be used to examine the case of demand among the rural Choma population. In particular, the sample gives an opportunity to highlight how different demand calculations can produce a range of results.

For this work, two different metrics are shown for determining daily firewood demand (C, in kg) among rural Choma households[2]. The first metric is a simple product of daily mean per capita firewood use (C_{cap} in units kgcap^{-1}day^{-1}) and rural population (P_R) (Equation 2).

$$C = C_{cap} \cdot P_R \qquad (2)$$

The second metric is a weighted sum (C_W, Equation 3). Here, the distribution of household sizes in Choma (n = 140) are used to allocate the total rural population (P_R) to a given household size (p_{HHSize_i} = percent of distribution with household size i). Each population of a given household size is then multiplied by the estimated per capita daily use rate for an individual in a household of that size, as determined by the equation fit to the case study data (Figure 12 and Equation 1). Firewood consumption for rural Choma is the sum of consumption across each household size. In the case of the Choma subset, the number of household sizes (n) is 29.

[2] The rural population of Choma used for this calculation is the de jure measure from the 2010 Census: 185,525

$$C_W = \sum_{i=1}^{n=29} (p_{HHSize_i} \cdot P_R)(8.667 \cdot HHSize_i{}^{-0.785}) \qquad (3)$$

Solving Equation 2 using the mean daily per capita firewood weight of 1.843kg yields an aggregate demand of 341,923 kg day^{-1} for rural Choma. Solving Equation 3 yields a demand of 330,961 kg day^{-1}. The difference between these figures is equal to 10,962 kg day^{-1} or 4,001 Mg annum^{-1} for the rural Choma population, a difference of 3.21%. To give perspective, an estimate of aboveground wood biomass for dry miombo woodland states an average of 58 metric tons of cord wood and 8 metric tons of brush per hectare (Chidumayo, 1997). This values the difference between the two estimates at 60.6 hectares of woodland per year, about .6 km^2, or 500.1 hectares of brush per year, about 5km^2.

5 Discussion

5.1 Connecting scales of analysis – regional and household trends in firewood use

Throughout this paper there has been a focus on multiple spatial scales of analysis and how they may influence the observed relationship that households have with the resources they rely upon to support their basic livelihoods. This relationship was examined through three spatial lenses: a literature review of results from case studies throughout southern Africa, a district-level aggregate of households across Zambia, and a household level assessment of firewood use in a single district. Together these investigations have highlighted the fact that individual household use practices are likely to be similar within a region compared to other regions, but that there is still a wide distribution of use rates within a region. In this way, household level variability in firewood use is framed by spatially broad landscape and cultural factors, while household composition is a primary contributor to variability within the local distribution.

Efficiencies in household size across samples

A reasonable question to ask at this point is whether or not the relationship between household size and per capita use is consistent across samples. That is, would a similar trend in efficiency with household size be detected when looking across multiple case studies? There has been some recognition that the household efficiency of firewood per additional household member was frequently true within a sample, but across samples the notion did not hold (Kituyi et al, 2001). On the other hand, an early example in the literature that recognized household efficiency in the realm of fuelwood consumption described the trend in efficiency at the aggregated village level among villages in Tanzania (Fleuret, 1978).

To investigate whether this trend existed across samples, the same per capita annual consumption rates derived from the literature review (Figure 2) has been plotted against the average household size reported in each study. The result is shown in Figure 15. Upon visual inspection, the relationship shown in Figure 12 (Chapter 4) does not appear to exist across studies throughout the SSA region.

It can be assumed that the trend of household size efficiency is not apparent across case studies because the distribution of household responses from the studies have been averaged and are represented by a single point with two mean characteristics. Indeed, one may suspect that Figure 15 above *may* consist of, within each of the case study points, distributions similar to that seen in Figure 12.

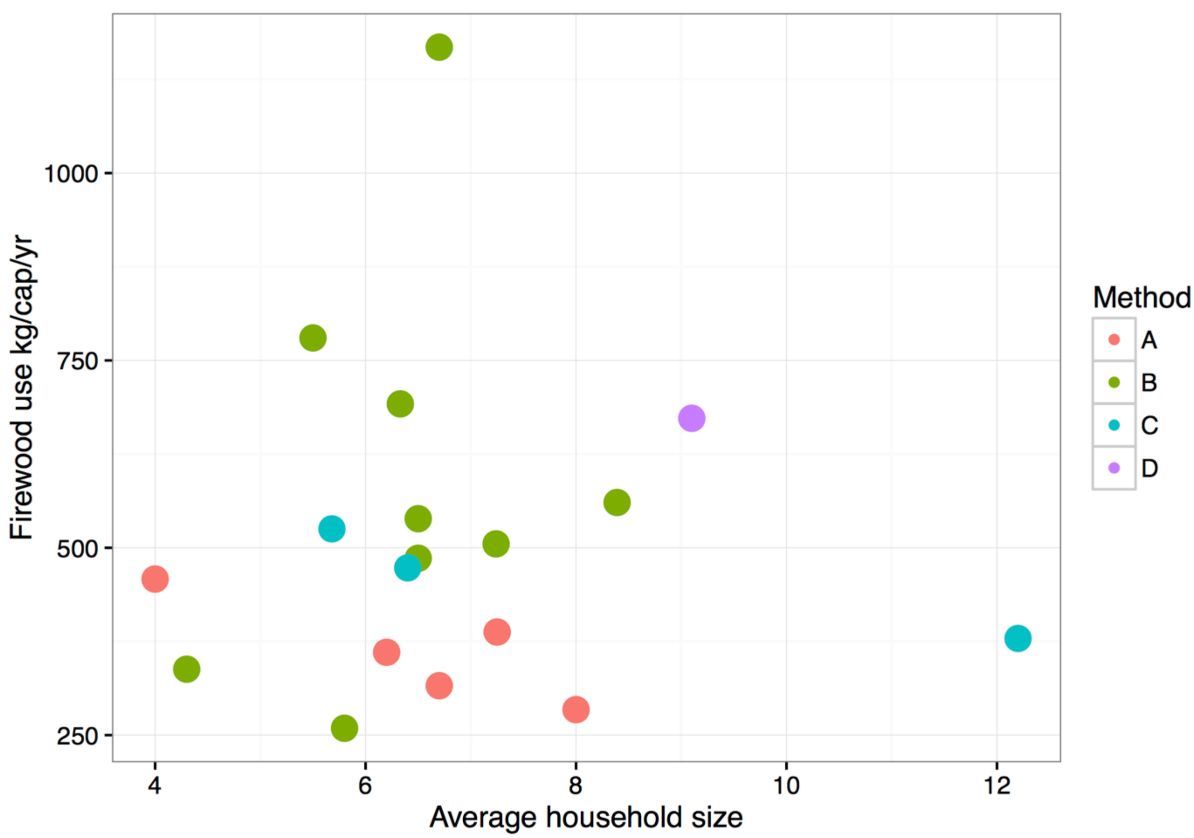

Figure 12 *– Literature review of per capita use/year and Household Size; A: proxy, B: self-appraisal, C: first-hand, D: firewood selection exercises*

There is additional evidence in the literature for the assumption that fuelwood efficiency with household size occurs within a sample, but not necessarily across samples. A study comparing households in two villages, one in Malawi and one in Tanzania, in a dataset from 1993-1994 found that the Malawian site demonstrated a household economy of scale very similar to the one found in the Choma sample, but the Tanzania site offered no such trend (Biran et al., 2004). Both points are plotted in the above figure.

It seems natural that each location should have a trend in household use efficiency that is similar to the one found in the results of the current paper. Several questions may then stem from this notion. What might be the cause of a sample that does not hold true to the household size efficiency trends, as in the Tanzania sample from Biran et al., 2004?

Beyond this, there are several open questions that could benefit from a comparison of studies in which the trend is detected. What might drive a change in the y-axis of the trend (greater firewood use throughout the sample)? What might change the shape of the curve that is represented by the exponent (different rates of efficiency)? Or, is the shape of the curve different for different fuel types? Answering these questions is beyond the scope of the current research but would provide further insight into fuelwood consumption dynamics.

An ad hoc aggregate demand assessment

The notion that household composition may drive household per capita firewood use can help to develop better aggregate assessments of firewood use. It has been acknowledged that data collected for this research cannot accurately assess the entire demand placed on forest ecosystems in Choma through human appropriation (contributors to demand not covered in this work include but are not limited to: land use change and agricultural expansion, charcoal use and production, fuelwood used for cottage industry, and timber harvested for construction). However, it is useful to examine how estimates of aggregate firewood demand may change by incorporating household composition into the calculation. The long history of incorrectness in assessments of the fuelwood supply-demand relationship has been addressed throughout this paper. However, at the risk of perpetuating this tendency, some simple aggregate measures of firewood demand in Choma were calculated for this research. The purpose here is to show not how much firewood is being removed for human use, but to show how much this assessment can vary based on method of calculation.

Equations 2 and 3 in Chapter 4 did not give astonishingly different measures of annual aggregate use for Choma district, but the difference itself is meaningful. Often, assessments of supply and demand assume that there is a difference threshold that separates the sustainable from the unsustainable. If such is to be the case, the uncertainty in a single metric or the variability between different metric calculations should be expressed.

Implications of demographic change

It is by now clear that both household and per capita measures of firewood consumption are closely related to household size. Data for the district level analysis suggests that some districts may have different household size distributions from one another. Figure 13 gives histograms for household size distribution in the 12 sampled districts. Household size is often related to individual and societal cultural, economic and demographic factors, among them being the need for household labor, maternal health, and marriage structure. The ability of a household to manage its size in a way to meet its economic and resource challenges is closely tied to its overall livelihood.

Population trends in Southern Province (where Choma is found) indicate that while populations are growing, household sizes have decreased somewhat (Table 6). From these data, the total number of households in the province can be estimated and it can be seen that this number is also increasing.

Table 6| *Southern Province population and household composition trends 1980-2010; figures provided by Zambian Central Statistics Office and derived from census data*

	Population	Population Density	Household Size	Number of Households (estimate)
1980	671,923	7.9	5.8	115,849
1990	965,591	10.6	6.6	146,301
2000	1,212,124	14.2	5.5	220,386
2010	1,589,926	18.6	5.4	294,431

This trend of increasing numbers of households and decreasing household sizes is occurring throughout Africa, and is particularly concerning for areas that may be rich in biodiversity (Liu et al., 2003). In this regard, fuelwood use seems likely to grow faster than proposed in some assessments that assume a linear relationship between population and fuelwood demand. The population effect on resources is often double in these cases as recurring household resource needs increase, but discrete needs – such as the need for materials for home construction – also increase.

5.2 Study limitations

A theme throughout this research has been the difficulty in producing reliable aggregate assessments of fuelwood use, and how issues in reporting methodology and household level variability underlie this phenomenon. While the new method of reporting fuelwood consumption presented in this paper improves on previous methods, there are many limitations of the research, both in how the work was carried out and how the resulting data is implemented.

Figure 2 in Chapter 2 characterized case studies from throughout the literature and emphasized the difference in reporting methodology among them, as well as the challenges of reporting firewood use in a consistent fashion throughout the literature. The approach presented in this paper is not unique among these studies in having a context that might not be easy to compare across space and time. This is due to many of the limitations that have long dogged case based research.

There are some limitations specific to the case of Choma. For instance, the firewood consumption measures were taken at a single time of the year, but temperatures in Zambia fluctuate seasonally, with a mean range of 15°C -27°C in the Zambian winter and 27°C -32°C in the dry summer (Jain, 2007). Prior research has found that household fuelwood use is consistent across seasons (Dovie et al., 2004), so it is unlikely that the regression results here would have been adversely affected by the time of year that the study took place. However, in assessing annual total fuelwood use from the reported data, total weight may have been over-estimated by using results reported in the coldest months.

This study was also limited to addressing the issue of firewood collection and use. Chapter 2 presents a good argument for this approach, focusing on the ubiquitous nature of firewood use and the burdensome impact that the collection has on the lives of rural farmers. However, any assessment of the true environmental burden of fuelwood in Choma would have to consider the production of charcoal. Charcoal is more biomass intensive in its production than firewood collection. It is also likely that production of charcoal will increase in the coming decades, both because of an increasing urban population and potential increasing use of charcoal by rural households. It is not unlikely therefore that charcoal may eventually outpace firewood use. This would be to the benefit of household labor, but would increase ecosystem disturbance and possibly deforestation. Along these lines, a more inclusive assessment of the total need for forest materials in Choma district would include wood products for construction purposes and for cottage industry (such as brick making or tobacco curing). Charcoal and small industry will be the primary deforestation drivers in the foreseeable future, while understanding firewood use is more critical to improving the livelihoods for the poorest of rural households and understanding their energy needs and limitations.

Statistical models of household and per capita firewood use were produced based on independent variables that have been consistently tied to household energy use for fuelwood users. In crafting these models, there is always a tradeoff between efficiency and over fitting, as such, the dependent variables were limited as much as possible. Still, there is a great deal of variability in the reported firewood use dependent variables that is not accounted for. Some of this variability could be considered randomness. Some likely has to do with the limitations of the reporting method.

Then, there is a segment of unaccounted variability that is likely to be measureable, but was not measured in this study for a variety of reasons. Part of this variability is to be found in the act of cooking. The history of cookstove development projects tells us not to ignore the element of lifestyle and preference in understanding fuelwood use (Crewe, 1997). Though no households in this study used improved cookstoves, even the common three-stone stove can have a range of efficiency depending on its construction and surrounding environment. One study found that the thermal efficiency of firewood burning on a three-stone stove ranged from 11-36% when measured directly from the stove (Menendez and Curt, 2013). Along these same lines, the type of food or typical diet of the household will determine how long food needs to cook or what techniques need to be used in cooking. For this, one cannot simply include dietary diversity into the regression; beans and greens are not the same here.

Within the model, there are some surprising results that need to be addressed, particularly in regard to unexpected relationships or significance of independent variables. The significance and the sign of the forest land cover dataset is the most outstanding case of unpredicted variable behavior. In developing the forest cover independent variable for the model, 2 different raster datasets of forest cover were tested at 3 different window sizes around the household. Each of the 6 resulting measures for the household had a significant negative relationship with firewood use (Figure 14). The two raster datasets used to explore the household-forest cover relationship were: a.) the land cover set included in the final analysis with a 40% canopy cover threshold and b.) a forest density metric, in which $90m^2$ pixels represent aboveground biomass densities of Mg ha^{-1}. Ultimately, the forest cover dataset was used, as the methods of derivation are documented in published literature (Sweeney et al., 2015). At the per capita level, the relationship between use and forest cover was less robust, but still appeared significant in the regression.

There are a number of potential cases that may have resulted this trend. The first possibility is that the relationship truly does exist and that households in more forested areas use less firewood than those in less forested areas. Two potential theories could emerge from this notion: a.) households in forested areas act as *stewards* to the forest and there is a reciprocal relationship between stewardship and forest quality or b.) households in less forested areas are indulging in classic 'tragedy of the commons' type behavior in which the scarcity of trees encourages them to use the resource while it is still available.

The second possibility is that the relationship is composed of one or more issues in the research structure. The first possible issue is that the forest land cover dataset (or the alternative forest density dataset) doesn't accurately represent the useable firewood for the area. The land cover dataset uses a threshold for forest canopy cover of 40%. This threshold is in line with many of the most popular global datasets today, however this threshold tends to underrepresent areas useable for firewood because miombo tree cover rarely exceeds 40% (hence the low forest land cover percent within 4.5km of the household in this study). This is a known issue with the most popular global forest datasets derived from Landsat imagery (Sexton, 2016). Additionally, households will use woodlands of a much lower canopy cover for collecting firewood and may be just as likely to use wood from individual trees than the forest itself (Mahiri & Howorth, 2001).

The second issue that may be influencing the relationship between forest cover and household firewood use in the regression is in the sample statistics. There simply are not that many observations at the higher forest land cover percentages. As such, the range of firewood use rates at lower forest cover levels is larger than those at higher forest cover levels, which may lead to an observed negative relationship (Figure 14).

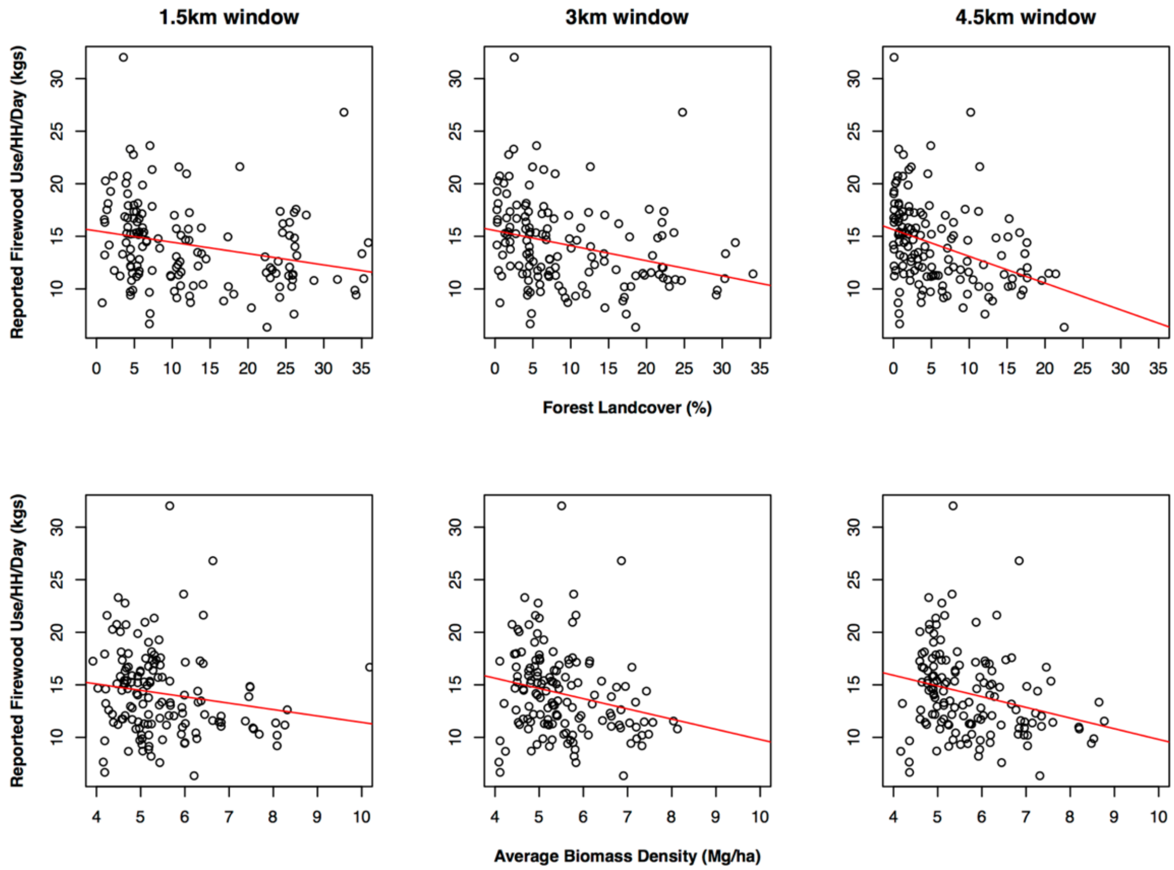

***Figure 13** – Forest cover metrics and household firewood use correlations*

A third condition that may be at play in the high significance of forest cover in the regression is the role of protected areas. A comprehensive spatial dataset of protected area boundaries for Choma district is unavailable, and protected areas may be enforced by a wide variety of parties (or not at all). It is possible however that those households in more forested areas are proximate to protected areas. This may influence the forest cover around the household, but may also limit the access to forested areas, making labor inputs for firewood collection greater.

The firewood selection exercise

The firewood selection exercise is a new way of determining household firewood use in remote areas. This method provides some improvements to the most common methods, not all of which have been implemented in this paper. However, determining household firewood use is a difficult task and there are some serious limitations to the method presented in this work.

First, the method is labor intensive and difficult. Weighing, measuring and determining the species for each stick in a single bundle takes the better part of a day. The method is also not highly scalable and producing several bundles was no easier than producing the first. There is the added challenge of transporting the bundle. Researchers in this study could not avoid transporting the bundles by foot, sometimes for long distances between households that were far apart. Add to this the problem of sticks in the bundle deteriorating with use and the process will easily occupy almost all the time of even the most efficient field researcher.

There is also the issue of the exercise itself. Marketing and cognitive science studies have found that, estimating volume is among the most difficult visual assessments, and people are not very good at it (Cleveland & McGill, 1985). This may be less of a problem for people with a great deal of experience using or handling the object though, and preparation for this study sought to get responses from the most experienced cook in the household. Many participants did appear to make judgments on firewood quality when choosing wood pieces for the reporting however, and responses to the longer survey suggests that many cooks do have species preferences. Investigating the tendency of households to choose preferred species could be an interesting direction for future research.

6 Conclusion

6.1 The fuelwood SES across scales of analysis

A fundamental objective of this work has been to examine the uncertainties inherent in the fuelwood SES, but to also acknowledge the inaccuracies that arise in SES studies due to structural challenges of science in the SES field. Central to the challenges of SES science is the translation of case study data theory building and policy implementation. In this work, the challenge of navigating the transition between case and application has been addressed in the interpretation of information between scales of analysis. Work for this research has highlighted the regional differences in collection practices throughout Zambia and how when examining more closely within a region, more nuanced trends of human behavior in resource use may emerge.

By exploring different methods of calculating aggregate fuelwood use for the rural Choma population, this paper presents a critical look at translating information between scales, and how data collected at a local scale can take a wide variety of paths toward generating an aggregate consumption measurement. This does not do much to assuage the foundational uncertainties of SES work across scales. Which metrics are considered when estimating the energy needs of a population, or the potential sustainability of the fuelwood SES in a given region, is ultimately at the discretion of the researcher. Work presented here suggests that household composition would be very important in such applications. Other researchers using other case studies may find that different trends are more important in furthering their domain of SES theory, and they may also produce accurate results. A goal for SES science should be to both embrace the challenge of incorporating widespread complexity while also increasing the applicability of SES studies by generating more accurate assessments of real-world systems.

It is critical to obtain consistent and uniform data to provide insight into the dynamics of the fuelwood SES. Better data collection will aid in the generation and defense of theories that may help to improve policy and understanding. Widespread disagreement or mismatches in how case studies are carried out and how data is collected may doom SES scientists to inefficiencies, duplications and incompatibilities of data in the open science world. For the most part these data difficulties can be overcome with ingenuity and communication. In the fuelwood SES the easiest method of determining demand is through proxy measures of fuelwood use. If the proxy method continues to be broadly used, researchers should simultaneously make consistent attempts to measure fuelwood use through direct observations. Such direct observations will allow for an on-going assessment of the proxy methodology – improving which questions should be asked and how they should be worded may be lead to sustained improvements in proxy estimation capabilities.

6.2 Future directions

In Chapter 2 of this paper the fuelwood SES was framed as being a critical component of the food-energy-water (FEW) nexus. Fuelwood is nested within the nexus at both the household and the landscape scales. African farmers rely on savanna resources to produce energy, while savannas are an inherently dynamic system, shaped by complex interconnected feedbacks in the realms of climate, land use, and disturbance. As farmers must make tradeoffs in the distribution of labor to various FEW tasks, so too must they negotiate the landscape to provide compromise in access to FEW resources. Further research into the direct and indirect tradeoffs within this system are critical to the incremental improvements that can help subsistence farmers be more productive with better livelihoods. Fuelwood consumption makes up such an important part of the household nexus because of the time and labor involved in generating the basic energy source.

Exploratory research during field work for research presented in this paper found that water use (liters collected per day) showed a mostly linear relationship with firewood consumption. Volumetric assessments such as the one presented here may also be useful for determining maize and water consumption. A selection or volume assessment technique that incorporates all three resources may help to evaluate the presence of tradeoffs at the household level that stem from landscape level access.

Population structure, both within the household and the distribution of household structures within a population, has been shown through this work to be deeply tied to resource use in the fuelwood SES. As populations in Africa grow and household sizes decrease, more energy use and less energy efficiency across the total population can be expected. Improvements in spatial datasets of population distribution in rural Africa are receiving research attention, and advances here will bring greater accuracy to total resource demand on the landscape.

Firewood consumption, per capita firewood consumption, and the fuelwood SES in general should be a focus of social science and environmental research for some time to come. Despite the major advances in energy production and consumption technologies throughout much of the world, most of Africa and many other places in the word depend on this resource for daily tasks. Major structural changes to the way Africans generate or use energy may come – but to predict or anticipate their arrival would be a disservice to the improvements that knowledge generation in the fuelwood SES could bring today. This paper has steered clear of policy prescriptions, mostly because the lives of rural firewood users seem largely untouched by any formal systems of governance that may favor the influence of research in this domain. Future research however may want to address policy implementations more directly. A valuable question to investigate is what level of improvement rural peoples lives may see by through a shift from firewood to charcoal. This is not a popular question to ask because of the implications that widespread charcoal production may have on savanna ecosystems. Most published literature seems to portray charcoal use negatively, because of its association with forest degradation and in-home air quality. However, the gains in quality of life from reduced labor in the production of household energy associated with the switch from firewood to charcoal may not be insignificant in many people's lives. Policy discussions in the charcoal domain are heated. Charcoal producers are more often painted as criminals than as service providers or entrepreneurs. Work could be done in this realm to examine what opportunities are to be found in making charcoal production more sustainable, more productive and less deplorable.

In future research, information and communication technologies (ICTs) may go hand in hand with high quality proxy questions for a real-time glimpse of how the fuelwood SES is dynamic through time, or how individuals may change their use behavior based on new conditions. Use of ICTs, and cell phones in particular, are proliferating throughout Africa (Poushter & Oates, 2015). As more Africans become integrated with the global information system, there may be more opportunities for them to contribute data on a wide variety of physical and social aspects of their lives. Integrating high frequency human response data and near real time remote sensing analysis will bring SES science closer to understanding the complex relationships between society and the landscape.

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Appendix A - Literature Review Table

Source	Study location	Sample size (households)	Consumption reported	Method	Notes on consumption method	Consumption in perCapita/year	Household Size in sample
Hoffmann et al., 2015	Tanzania, South-Western	n = 160	6,489 MJ/cap/year	Proxy	'energy assumption of 18MJ/kg firewood'	360.5	6.2
Menéndez and Curt, 2013	Tanzania, Iringa Region	n = 20	0.71kg/cap/day	Self appraisal	'Household fuel consumption was evaluated during the household interview, from the amounts that respondents said the family consumed over the specified time, followed by weight evaluation'	259.15	5.8
Scheepers et al., 2013	South Africa, Limpopo Province, Bela-Bela town	n = 100	1833.12 kg/hh/year	Proxy	Product of average mass of fuelwood per fire and frequency of fires in winter/summer seasons	458.28	4.0
Madubansi, et al., 2007	South Africa, five rural villages	1991: n = 356 2002: n = 399	44.9 kg/cap per month in 2002; 40.5 kg/cap/month in 1991	Self appraisal	'The respondents were asked to estimate the amount of fuelwood used on a daily basis and this was weighed and recorded'	1991: 486 2002: 538.8	1991: 6.5 2002: 6.5
Shackleton et al., 2007	Eastern Cape Province, South Africa	n = 205	1454kg/hh/year	Self appraisal	'they were requested to set aside the amount of wood they typically used within a day, which was subsequently weighed using a spring balance to the nearest 0.5 kg'	338	4.3[a]

Dovie et al., 2004	South Africa, rural	n = 45	692 kg/capita/year; 4343 kg/HH/year	Self appraisal	'amount of wood used daily, expressed as stick counts and/or in wheelbarrow loads. These were counted and weighed on a per household basis'; finds winter and summer use rates are highly correlated	692	6.33
Brouwer & Falcão., 2004	Mozambique, Maputo, the capital city	n = 240	0.9-1.0 m3/cap/year; 5.8kg of firewood/hh/day	Proxy	'One of the difficulties of previous surveys is the quantification of consumption. Questionnaires by their nature rely on the memories and estimates of respondents and only in exceptional cases is it possible to actually measure consumption. Moreover, frequently the quantities are measured in highly variable and non-precise units such as bins, bundles, etc'	315.97	6.7[a]
Biran, A et al., 2004	Two villages; Malawi and Tanzania	Tanzania: n = 69 Malawi: n = 60	Tanzania: 9.1kg/cap/week Malawi: 10.1 kg/cap/week	First hand accounting	In Malawi: 'Firewood consumption was monitored monthly over a period of seven consecutive days… On the first day the household firewood stockpile was weighed. On each of the 7 days, all firewood bundles collected or bought by the household were weighed and an estimate of the weight of any wood that had been sold or donated to other households each day was recorded. The stockpile was	Tanzania: 473.2 Malawi: 525.2	Tanzania: 6.4[a] Malawi: 5.68[a]

					reweighed at the end of the seventh day. ' In Tanzania: 'When wood was brought to a house the identity of the person bringing it was recorded and the bundle was weighed using a spring balance.'		
Tabuti et al., 2003	Uganda, Bulamogi county	n = 126	35-52.5 kg/hh/week; 228-341 kg/cap/annum	Proxy	Respondents were asked how many headloads were used per week; 'The interviews were supplemented by direct observations and measuring the weights of bundles of firewood (n=4)'	228-341	8
Kituyi et al., 2001	Kenya, 13 study sites	n = 2202	0.8-2.7 kg/cap/day	Self appraisal	'…interviewed household heads or their representatives and weighed the presumed daily household biofuel needs using a weighing balance'; '3–5% of households per station were subjected to actual consumption experiments, in which an enumerator weighed the actual biomass burnt in each of the several daily combustion sessions'	780	5.5
Vermeulen, S. J. et al., 2000	Zimbabwe, nine study sites	n = 1500	2.81 tonnes/hh/year	Proxy	2.81 is the 1999 result for 'exclusive firewood users further from urban centers'; 1994 figures for the same sample type are 3.84 tons/hh/year	387.59	7.25
Benjaminsen, T. A., 1997	Mali, southern	n = 67	1.04 kg/cap/day	First hand accounting	'a part of the household's stock of wood was weighed on the morning using a spring balance.	379	12.2

					The woman cooking that day was asked to burn wood from that bundle only. At the same hour the next morning the stock was weighed again and one day's consumption could be calculated'		
Marufu et al., 1997	Zimbabwe, five study sites	n = 519	3.2 kg/cap/day	Self appraisal	'the survey-execution phase involved interviewing respondents and taking weights of biofuel which respondents suggested would be typical of their normal daily energy requirements'	1168	6.7
Banks et al., 1996	South Africa, The Mhala region, two villages	Athol: n = 70 Welverdiend: n = 69	Athol: 505.2 kg/cap/year Welverdiend: 560.4kg/cap/year	Self appraisal	'An individual at each household, usually the person responsible for most of the cooking, was requested to set aside what they considered to be the household's daily fuelwood requirement, which was then weighed'; 'daily wood consumption by ten households in Welverdiend was monitored for a period of 8 days, and compared to prior estimation of wood use.	Athol: 505.2 Welverdiend: 560.4	Athol: 7.24 Welverdiend: 8.39

[a]For these studies, household size was not explicit in the text and was calculated by context.

Appendix B - Survey Materials: Firewood Selection Exercise

Camp Name:
Village Name:

Number of Household Members:
- Total:
- Children 0-5:
- Males 5-15:
- Females 5-15:
- Males 15+:
- Females 15+:

How long does it take to travel from the household to the following locations on foot (enter all in MINUTES):
- Tarmac road:
- Public Transportation:
- Village market:
- Water collection location:
- Firewood collection location:
- Primary maize field:

What is the bearing of the direction that the household goes to collect firewood? (0-360)

Which wood bundle is being used for this survey?

Which of the following fuels have you used for cooking in the last 6 months?
- ❑ Firewood
- ❑ Charcoal
- ❑ Electricity
- ❑ Liquid Propane Gas (LPG)
- ❑ Animal Dung
- ❑ Crop Residues
- ❑ Other

In the last 7 days, how many days have you used charcoal for cooking?

- ❍ 0
- ❍ 1
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6
- ❍ 7

Who is the primary collector of firewood for the household?

- ❍ Self
- ❍ Spouse
- ❍ Son
- ❍ Daughter
- ❍ Granddaughter
- ❍ Grandson
- ❍ Father
- ❍ Mother
- ❍ Brother
- ❍ Sister
- ❍ This household purchases firewood and does not collect it

How do members of this household collect firewood (check all that apply)?

- ❑ Headload
- ❑ Shoulderload
- ❑ Ox cart
- ❑ Bicycle
- ❑ Other ____________________

How many times is firewood collected per week for the household?

Is firewood harvested from the same general location every time?

How much time does someone from your household usually spend in collecting firewood during a given trip? (Time spent walking both ways, and collecting, in minutes)

What do you see as the primary obstacle in collection of firewood?

- ❍ Distance to collection area
- ❍ Density of available firewood
- ❍ Someone with time to do the collection
- ❍ Poor quality of available firewood
- ❍ Limitations of access/protected area
- ❍ Other ____________________
- ❍ No significant obstacles in finding firewood

Is it difficult to find firewood for cooking in the wet season in this area?

- ❍ Yes
- ❍ No

Are there members of this village that produce charcoal for sale?

- ❍ Yes
- ❍ No

During what months did you produce charcoal?

- ❑ June 2015
- ❑ July 2015
- ❑ August 2015
- ❑ September 2015
- ❑ October 2015
- ❑ November 2015
- ❑ December 2015
- ❑ January 2016
- ❑ February 2016
- ❑ March 2016
- ❑ April 2016
- ❑ May 2016
- ❑ June 2016
- ❑ Did not produce

Where did you market your charcoal production in the last year?

- ❑ Neighbors
- ❑ Along Roads
- ❑ Nearby Markets
- ❑ Middleman
- ❑ Other

Does the household practice any of the following in the collection of firewood? (check all that apply):

- ❑ Limbing/lopping
- ❑ Girdling
- ❑ Chopping of entire trees

How has firewood availability near the household changed in the last 10 years?

- ❍ Increased
- ❍ Stayed the same
- ❍ Decreased

Are there tree species that were available 10 years ago that are no longer available? (If yes, please specify)

- ❍ Yes ____________________
- ❍ No

What has been the impact of the following types of disturbances?

	Significant impact	Slight impact	No impact
Fires	❍	❍	❍
Clearing of forest for agricultural lands	❍	❍	❍
Clearing of forest for charcoal production	❍	❍	❍
New restrictions to access/protected areas	❍	❍	❍
Increased demand on firewood collection area	❍	❍	❍
Other	❍	❍	❍

Are there areas nearby where you are not allowed to collect firewood?

- ❍ Yes
- ❍ No

What is the reason for not being allow to collect firewood in the restricted area?

Who is responsible for the area where you usually collect firewood?

- ❍ National Government
- ❍ Local Government
- ❍ Traditional Land/Traditional Authority
- ❍ Myself / my household
- ❍ Private Individual (family)
- ❍ Private Individual (not related)
- ❍ Other ____________________

Does the household have any preferred species of wood for use in cooking? List them here:

We will now commence with the firewood selection exercise. Please explain to the respondent the purpose of the exercise.

Bundle []: Which wood pieces were selected for use in cooking a typical breakfast for the household?

Bundle []: Which wood pieces were selected for use in cooking the typical mid-day meal for the household?

Bundle []: Which wood pieces were selected for use in cooking the typical evening meal for the household?

Does the household use firewood in preparing any additional meals in a typical day?

- ❍ Yes
- ❍ No

Are the wood bundles that are collected at this household generally similar in size to this bundle?

- ❍ This bundle is smaller than what the household usually collects
- ❍ This bundle is about the same size as what the household usually collects
- ❍ This bundle is larger than what the household usually collects

Are the wood pieces that the household collects generally similar in size to the wood pieces in this bundle?

- ❍ No, the household typically collects larger wood pieces
- ❍ Yes, these pieces are of similar size
- ❍ No, the household typically selects smaller pieces

Of the last 7 days, how many days has the household used firewood for the following activities?

	0	1	2	3	4	5	6	7
Space Heating	❍	❍	❍	❍	❍	❍	❍	❍
Heating water for baths	❍	❍	❍	❍	❍	❍	❍	❍
Heating water for other reasons	❍	❍	❍	❍	❍	❍	❍	❍
Ironing	❍	❍	❍	❍	❍	❍	❍	❍
Other:	❍	❍	❍	❍	❍	❍	❍	❍

Appendix C - District Descriptive Statistics Tables

Table C1 | Population and land area[a]

		n	District area (km²)	Population (2010)	Rural population (%, 2010)	Population density (2010)
1	Choma	263	7,296	247,860	76.27%	34.0
2	Lundazi	84	14,058	323,870	95.09%	23.0
3	Masaiti	78	5,383	103,857	97.98%	19.3
4	Mbala	80	8,339	203,129	88.18%	24.3
5	Mkushi	94	17,726	154,534	87.58%	8.7
6	Mpongwe	80	8,339	93,380	83.96%	11.2
7	Mufumbwe	80	20,756	58,062	83.51%	2.8
8	Mumbwa	85	21,103	226,171	86.28%	10.7
9	Chinsali	88	15,395	146,518	89.63%	9.5
10	Namwala	91	5,687	102,866	94.75%	18.1
11	Petauke	69	8,359	307,889	90.35%	36.8
12	Solwezi	84	30,261	254,470	61.99%	8.4

[a]all column figures reflect those given by the CSO of Zambia and reflect results from the census of 2010

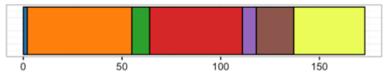
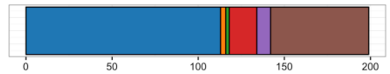
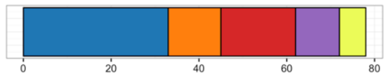
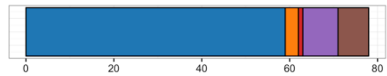
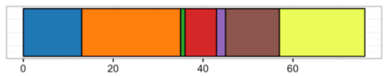
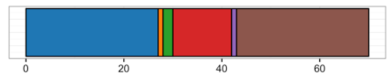
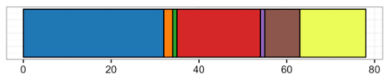
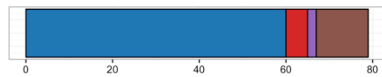
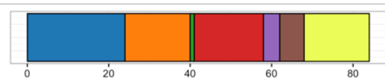
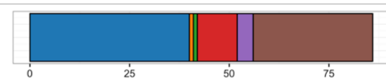
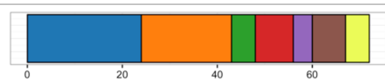
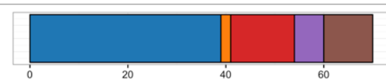
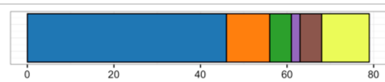
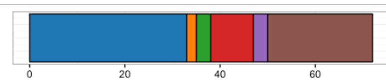
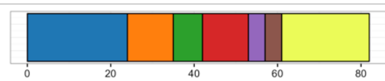
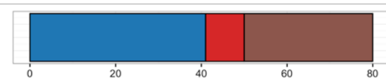
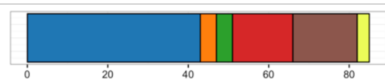
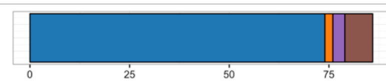
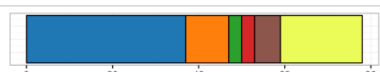
Table C2 | District Household attributes

	Household size (sd)	Reported median income (Zambian Kwacha)	Reported median landholding (ha)	Language group
Choma	7.98 (3.75)	3000	4	Tonga
Lundazi	5.61 (2.23)	850	3	Tumbuka
Masaiti	6.59 (2.92)	4775	3	Bemba
Mbala	5.40 (2.40)	2475	2	Bemba and Mambwe
Mkushi	6.95 (2.85)	6720	1.675	Bemba
Mpongwe	6.43 (2.95)	4100	3	Bemba
Mufumbwe	7.24 (2.91)	1250	2	Kaonde
Mumbwa	6.51 (2.95)	4200	3.8	Tonga (highly mixed)
Chinsali	5.51 (1.99)	1690	1.75	Bemba
Namwala	7.34 (3.55)	4045	4	Tonga and Ila
Petauke	6.16 (3.13)	680	2.8	Nyanja
Solwezi	7.69 (3.73)	8000	2	Kaonde, Bemba and Lunda

Table C3 | Firewood collection and use attributes

	Collections per week (sd)	Distance to collection, in minutes (sd)	Use of transport technology (%)	Charcoal users (%, six months)	Charcoal producers (%, one year)	Solar panel ownership (%)	Spent money on charcoal (%)	Spent money on firewood (%)
Choma	2.64 (1.48)	24.19 (28.36)	19.77%	22.28%	1.14%	33.97%	15.59%	4.94%
Lundazi	1.83 (1.48)	50.85 (52.19)	0.00%	19.28%	4.76%	10.84%	10.84%	10.71%
Masaiti	3.22 (2.06)	24.70 (26.75)	0.00%	67.53%	53.85%	21.79%	26.92%	1.28%
Mbala	2.17 (1.15)	50.13 (43.78)	25.00%	69.62%	16.25%	11.25%	47.50%	3.75%
Mkushi	2.18 (1.28)	30.10 (36.70)	25.53%	78.41%	28.72%	13.83%	47.87%	9.57%
Mpongwe	2.30 (1.59)	48.80 (39.38)	1.25%	72.50%	22.50%	16.25%	43.75%	13.92%
Mufumbwe	2.57 (1.57)	46.53 (41.30)	26.25%	34.18%	15.00%	15.19%	15.00%	1.25%
Mumbwa	2.37 (1.73)	29.74 (27.58)	42.35%	42.35%	10.59%	22.35%	14.12%	4.71%
Chinsali	2.12 (1.08)	47.56 (48.96)	0.00%	70.93%	23.86%	7.95%	36.36%	3.41%
Namwala	2.14 (1.57)	47.89 (52.54)	50.55%	26.67%	8.79%	15.56%	10.99%	14.29%
Petauke	1.75 (0.79)	59.74 (51.86)	0.00%	48.53%	4.35%	21.74%	30.43%	7.25%
Solwezi	2.47 (1.61)	46.79 (45.35)	47.62%	67.47%	28.57%	33.73%	41.67%	2.38%

Table C4 | Categorical collection variables

	Primary obstacle in collection	Firewood collection governance type
Choma		
Lundazi		
Masaiti		
Mbala		
Mkushi		
Mpongwe		
Mufumbwe		
Mumbwa		
Chinsali		
Namwala		
Petauke		
Solwezi		

Collection Obstacles:

Blue – Distance to collection location
Orange – Density of available firewood
Green – Someone with time to collect (labor)
Red – Poor quality of available firewood
Purple – Limitations of access to firewood collection location
Brown – Other
Yellow – No significant obstacles

Governance types:

Blue –Traditional authority
Orange –National government
Green –Local government
Red – Myself
Purple – Private individual (family or relative)
Brown - Private individual (not related)