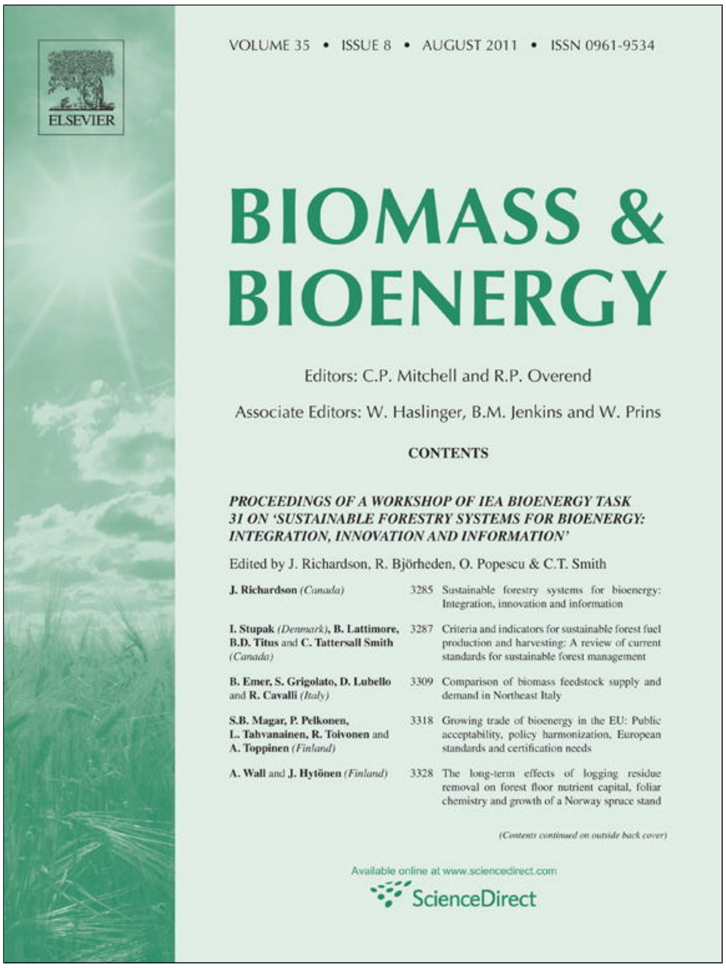

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CONTENTS

PROCEEDINGS OF A WORKSHOP OF IEA BIOENERGY TASK 31 ON 'SUSTAINABLE FORESTRY SYSTEMS FOR BIOENERGY: INTEGRATION, INNOVATION AND INFORMATION'

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Biomass availability, energy consumption and biochar production in rural households of Western Kenya

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ABSTRACT

Pyrolytic cook stoves in smallholder farms may require different biomass supply than traditional bioenergy approaches. Therefore, we carried out an on-farm assessment of the energy consumption for food preparation, the biomass availability relevant to conventional and pyrolytic cook stoves, and the potential biochar generation in rural households of western Kenya. Biomass availability for pyrolysis varied widely from 0.7 to 12.4 Mg ha^{-1} y^{-1} with an average of 4.3 Mg ha^{-1} y^{-1}, across all 50 studied farms. Farms with high soil fertility that were recently converted to agriculture from forest had the highest variability ($CV = 83\%$), which was a result of the wide range of farm sizes and feedstock types in the farms. Biomass variability was two times lower for farms with low than high soil fertility ($CV = 37\%$). The reduction in variability is a direct consequence of the soil quality, coupled with farm size and feedstock type. The total wood energy available in the farms (5.3 GJ $capita^{-1}$ y^{-1}) was not sufficient to meet the current cooking energy needs using conventional combustion stoves, but may be sufficient for improved combustion stoves depending on their energy efficiency. However, the biomass that is usable in pyrolytic cook stoves including crop residues, shrub and tree litter can provide 17.2 GJ $capita^{-1}$ y^{-1} of energy for cooking, which is well above the current average cooking energy consumption of 10.5 GJ $capita^{-1}$ y^{-1}. The introduction of a first-generation pyrolytic cook stove reduced wood energy consumption by 27% while producing an average of 0.46 Mg ha^{-1} y^{-1} of biochar.

1. Introduction

Biomass is one of the most important resources in smallholder farms in Africa. It provides rural households with ecosystem services such as soil organic matter, soil protection against erosion, nutrient recycling to crops, fuel, building materials and animal feed. In 2002, biomass also supplied 69% of the total energy used in rural households in Kenya [1]. The general trend in developing countries is for households to move up the "energy ladder" as income increases. Yet, in rural areas, low income and relatively easy access to free biomass, encourages the use of biomass as a source of cooking energy [2].

Rapid increase in soil degradation is a major threat to agricultural productivity in Africa [3]. Soil degradation can be set in motion by the conversion of forest and grasslands to agricultural lands [4–7] and the necessity to intensify cultivation on marginal lands. Such soil degradation often

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manifests itself through rapid decrease in soil organic carbon as a result of continuous cultivation, leading to a decrease in soil nutrient retention and supply [8]. The need to maintain both adequate soil organic carbon levels as well as provide biomass for household cooking generates biomass shortages in many rural communities and warrants technology development that makes better use of biomass resources.

Improved cook stoves have been developed over the past decades [2,9–11] that address issues of decreasing fuel wood supply. However, such cook stoves still rely on woody feedstock. An additional approach to conventional cook stoves based on biomass burning is the pyrolysis of biomass. Pyrolysis affords the possibility to expand the feedstock options, and utilize grass or crop residues to supplement woody biomass [12]. However, no information exists about the amounts of non-woody biomass on farms that could be used in such pyrolytic stoves. Furthermore, it is not clear to what extend other uses would limit the availability of biomass [13], such as the need for feed and fiber.

In addition to cooking energy, pyrolytic cook stoves also generate a solid by-product, biochar, which can be used as a soil amendment [12,14]. Biochar has been shown to improve soil fertility through various mechanisms and increase crop productivity [8,15,16]. Given the rapid decomposition rates of crop residues and manures in tropical soils [17,18] the much greater stability of charred biomass [19] affords the possibility to improve soil organic matter (SOM) levels and hence soil productivity on the long term. Yet, it is not clear, how much biochar can be produced through pyrolytic cook stoves.

Therefore, the objectives of this study were: (i) to quantify on-farm biomass resources in smallholder farms with potential use for biochar and bioenergy production using pyrolysis or combustion; (ii) to determine the current household cooking energy consumption with the use of traditional and pyrolysis stoves; and (iii) to assess biochar production using a pyrolysis stove. Our goal was to determine whether on-farm biomass production was capable of supplying sufficient fuel energy to sustain household cooking energy needs as well as of producing sufficient biochar by way of pyrolysis as a soil amendment.

2. Materials and methods

2.1. *Study area*

The study was conducted in Vihiga, South Nandi and North Nandi districts of western Kenya (39° 94′ 23′′E; 00° 13′ 44′N) [8]. The area ranges in elevation from 1,542 to 1,837 m above sea level [8]. Mean annual temperature is 19 °C and mean annual precipitation is approximately 2000 mm [20]. Rainfall is bimodal with a long rainy season (LR) from March to August and a short rainy season (SR) from September to January [8,21]. Farms selected for the study originally formed part of the Nandi forest. Because of land encroachment and increasing population, the forest is being cleared and converted into permanent agricultural land [21]. Farms in the area have high agricultural potential, but experience severe nutrient depletion. Kinyangi [20], Ngoze et al. [21] and Solomon et al. [7] reported decreasing soil productivity because of declines in SOM and nutrient contents after forest clearing. Farms in the area have been characterized as agroforestry systems [22] because they include small areas dedicated to livestock, wood production and other minor crops.

2.2. *Farm selection*

The farms for this study were selected from a sample of 260 sites established by Kinyangi et al. [20] and Marenya and Barrett [23] located in eleven sub-locations. These sites were originally established to conduct studies on the relationship between SOM and soil fertility; and were later included in a study about soil health and rates of fertilizer use. In total 50 farms were selected in a stratified random sample based on the year of conversion from natural forest to agriculture. These farms represent a chronosequence of land conversion from natural forest to continuous agriculture from 1900 to 2003. Each location includes a minimum of three farms per time of conversion across the entire chronosequence. Further classification was made in this study according to age; recent <20years, intermediate 21–50 years and old >50 years of conversion. We selected these years as cut-off points since organic carbon content and soil productivity dramatically changed between these periods [8,21].

2.3. *Farm description and biomass survey*

Household and farm data were collected with structured questionnaires on farm production and biomass use. Each farm was surveyed to identify farm and plot boundaries and biomass sources for potential use as fuel for pyrolysis. Data collected included: year of conversion from forest to agricultural land, type of crops grown, area of crops grown, use of soil amendments (manure and crop residues) and management of crops and other biomass residues. The farms in the study range in size from 0.25 to 5.67 ha with an average farm size of 1.68 ha. The typical farming household is composed of the homestead, centrally located and surrounded by ornamental and fruit trees. The remaining farm is divided into plots of different sizes. Main agricultural activity is cultivation of maize, intercropped with beans while the rest of the farm is subdivided into plots dedicated to production of bananas, collard greens, Napier grass, tea, woodlots and other minor crops. Vegetable gardens are usually the closest to the homestead, followed by plots used for subsistence production or food crops. Cash crops, such as tea are found the farthest from the homestead and at times established in different fields off the main farm. Woodlots are also established farther away from the homestead and are mostly composed of single species of fast growing trees. Other trees are found scattered within the farm, representative of the original forest vegetation before establishment of the farm. Boundaries of the farm are defined by shrubs or trees surrounding the perimeter of the area, serving as protection to the homestead, windbreak and fuel wood sources in scarce seasons [22,24].

2.4. *Aboveground biomass measurements*

For the purpose of this study, we measured the biomass of vegetation identified by farmers as sources of fuel for pyrolysis. Total aboveground biomass was measured for four major biomass classes; woody biomass, maize residues (cobs and stover), collard green stalks and banana pseudo stems. We identified 75 species of trees, of which 40 are considered useful as fuel by households (see supplementary online material).

For agricultural lands it was impossible to measure all biomass by destructive sampling. Therefore in some instances the use of allometry was necessary (see supplementary online material). Allometric relationships were used for woody and banana biomass estimates. Aboveground tree biomass was determined using relationships based on diameter at breast height (DBH) and tree height. For each tree, DBH was measured with a caliper or measuring tape with an accuracy of +/− 5 mm. The height of trees and terrain slope were measured with a Sunnto clinometer with an accuracy of 1%. Wood density values were obtained from the literature [25,26] according to species and location. Total tree dry biomass is usually calculated using site or species-specific allometric equations. To our knowledge, there are no published specific allometric equations for the area or all species of trees surveyed. Total tree dry biomass was calculated using a general allometric equation developed by Brown et al. [27] for moist life zone (1.5–4 m rainfall y^{-1}) and trees with $0.1 < D < 0.89$ m as:

$$B = 0.049\ \rho D^2 H \tag{1}$$

whereby D is the diameter at breast height in cm, H the tree height in m, ρ the wood density in g cm^{-3} and B the total biomass in kg per tree. For ease of measurements, we divided woody biomass into specific categories such as woodlots, windrows and scattered trees. All trees in the farms were inventoried and measured. For banana aboveground biomass all banana stems were measured. A tree-specific allometric equation developed by Arifin (2001) (cited in Hairiah et al. [28]) was used:

$$Y = 0.030 DBH^{2.13} \tag{2}$$

whereby Y is the total biomass in kg per tree and DBH is the diameter at breast height in cm.

Biomass of maize residues was estimated from secondary data collected by Kimetu et al. [8] and Ngoze et al. [21]. We used maize yields for the two main growing periods, long rains and short rains. For the long rains, data for two growing seasons provided estimates of maize stalks and cobs with no nitrogen fertilizer applications. Data for the short rains only included one growing season and residues were estimated from plots with no application of nitrogen or phosphorus.

Biomass of collard green stalks was measured from repeated sampling and destructive harvest. For each site, three 2 by 2 m plots were hand harvested and weighed in the field. Stalks were oven dried at 70 °C to a constant weight and dry weight determined.

2.5. Biomass stocks and productivity

Total aboveground standing biomass was calculated for each farm. Measurements of wood (woodlots, windrow and individual trees) were aggregated for each farm. Maize residues were disaggregated into cobs and stalks. Yields were calculated by season. The average of two growing seasons (2005, 2006) was calculated for the long rains. For the short rains only data for one season (2004) was available. Collard green stalk biomass was calculated as an average biomass of the three plots measured and banana stalks biomass was calculated on a per farm basis. Area measurements were taken for the whole farm and each cropped area by personally surveying each field.

Total biomass productivity was estimated on a yearly basis. Maize is an annual crop and bananas are perennials, however the productive capacity of each banana pseudostem occurs on an annual basis [29]. Therefore annual productivity was considered to be the same as standing stock. Collard greens are grown for a period of three months at a time. A total of four cropping seasons are obtained within a year. Productivity was calculated by multiplying average standing biomass of stalks times total cropping seasons.

Potential productivity of woody biomass was estimated using species and location specific mean annual increments (MAI) from the literature (see supplementary online Table S1). When no data was available for Western Kenya, we used MAI data for the general region of Africa. We used the data collected from the literature and on-farm measurements to develop an equation to calculate wood productivity. Tree productivity was obtained from the following equation:

$$P = \frac{M_{sp} * \mathrm{MAI}}{M_s} \tag{3}$$

whereby P is productivity in Mg y^{-1}, M_{sp} is total standing stock of each species in Mg, MAI is the mean annual increment of each species in Mg ha^{-1} y^{-1} and M_s is the standing stock of each tree species from the literature in Mg ha^{-1}. The biomass of wood, maize residues, collard stalks and bananas was aggregated, to calculate total standing stocks and productivity per individual farm, area and biomass type.

2.6. Available biomass energy for pyrolysis

Based on total aboveground biomass calculations, available biomass energy was calculated for each farm. Some biomass sources have competing uses within the farm. Using data collected during the initial biomass survey in the household, the percent of biomass used for other activities was subtracted from the total biomass estimates (see supplementary online Table S2). This resulted in total available biomass for pyrolysis use. In order to determine the energy available for pyrolysis in the farm, the total available biomass was multiplied by the heating value of the respective type of biomass. The following equation was used:

$$E_p = M_b * \mathrm{LHV} \tag{4}$$

whereby E_p is the energy available for pyrolysis in GJ, M_b is the total aboveground biomass and LHV is the low heating value energy content of the feedstocks determined by first measuring the high heating value using bomb calorimetry [30] and correcting for hydrogen content of the biomass (for results see supplementary online Table S3). Hydrogen was measured by Dumas combustion (Hekatch HT oxygen analyzer, Sercon LtD, Cheshire).

2.7. *Energy consumption for traditional and pyrolysis stoves*

The quantity of energy currently used for cooking was assessed through daily cooking tests in a randomly selected subsample of 20 households. Fuel wood and wood char residue measurements were made in each household during daily cooking activities with traditional stoves. Char is defined in this publication as the carbonaceous material remaining after combustion. For the pyrolysis stove (detailed description in supplementary online material), masses of fuel wood, biomass, wood char residues and biochar (the solid residue in the pyrolysis chamber) were quantified. A subsample of the fuel wood and biomass used was taken from each household to determine the moisture and energy content. Moisture content was determined by drying at 60 °C to constant weight. In addition the remaining wood char residue and biochar were also subsampled and measured for their respective energy content as described for the biomass (results in supplementary online Table S4). To determine the energy used per capita, we multiplied the amount of fuel wood used by the energy content and divided by the total amount of people in the household. The resulting energy consumption per capita serves as a baseline to compare the current energy consumption of the household and the consumption, when a pyrolysis stove is introduced.

2.8. *Statistical analysis*

Statistical analysis was accomplished with JMP version 8.0 [31]. Analysis of variance (ANOVA) was done to assess the differences of biomass productivity, energy availability for pyrolysis and energy consumption between age conversion categories. Biomass productivity variability between age conversion categories was determined using coefficient of variation. Mean comparisons was determined using the least square differences at $P<0.05$.

3. Results

3.1. *Aboveground biomass stocks and productivity*

Total aboveground standing stocks and productivity varied significantly with time since the land was converted from forest to agriculture (Fig. 1). However as time of land conversion increases, variability decreases, which was visible both per unit farm and area. The greatest variability was detected in total productivity per unit area which was significantly different ($P < 0.05$) across the different conversion age categories. Farms that were cleared 20 years ago or less, had the highest variability in productivity from 0.68 Mg ha^{-1} to 12.93 Mg ha^{-1} (CV = 0.83) (Table 1). Average aboveground productivity for farms that were recently converted from forest to agriculture (6.09 Mg ha^{-1} y^{-1}) was two times ($P < 0.0029$) the average productivity for intermediate (3.52 Mg ha^{-1} y^{-1}) and old conversions (3.02 Mg ha^{-1} y^{-1}).

3.2. *Biomass composition*

Plant species composition in the farms contributed significantly to differences in total biomass production. Standing biomass per unit farm ranged from 2.4 to 62 Mg farm^{-1}, with an average of 16.9 Mg farm^{-1}. When exploring the sources of variability there were clear differences in feedstock composition throughout the three different age categories. Farms under cultivation for less than 20 years have a lower proportion (45%) of wood biomass than old farms (70%) (Fig. 2). On the other hand the major proportion of standing biomass in younger farms is derived from maize residues, in the form of both maize cobs and stover (8% and 44%, respectively). Maize residue biomass in older farms (50 years or more) decreased by half ($P < 0.0018$). Therefore, as time of conversion increases the proportion of the type of biomass in the farm changes. The sources of biomass in younger farms were food crop residues, while older farms contained more wood biomass.

Biomass productivity also varied with feedstock type. The proportion of tree productivity did not differ significantly across conversion age. On the other hand, the proportion of maize residue productivity was larger for younger than older farms. Maize cobs contributed 11% and stover 63% to total production in recently converted farms, in comparison to 4.7% and 45% in old farms. Banana productivity contributes 18% of the total biomass for older farms, but 5% to that of farms that were cleared from forest less than 20 years ago. Consistent with results of standing biomass, the productivity of younger farms mainly results from maize residues, while that of older farms is more evenly distributed among feedstocks.

3.3. *Effect of farm size on biomass availability*

Standing biomass varied considerably in farms that were recently cleared from forest, but variability declined as farm size increased (Fig. 3). Biomass productivity also varies with farm size, and decreases sharply at a particular size. Farm productivity per unit area was twice the amount ($P < 0.0005$) for smaller farms up to 1 ha, when compared to farms larger than 2 ha. No significant differences were found in the proportion of biomass from each feedstock between farms of different sizes with maize residues being the largest portion across all farm sizes (Fig. 4).

3.4. *Available energy for pyrolysis*

On average 25% of the maize stover are used as animal feed and building materials, with the remaining 75% being usable for pyrolysis. An average of 8% of the banana biomass is fed to household animals (from 0 to 25%; supplementary Table 2). Taking into account, the biomass used for other purposes, we calculated the amount of energy from productivity, potentially available for pyrolysis (Table 2). Energy availability declined considerably on a farm and area basis across the different age conversions. Young farms have more available energy than the older farm and variability is less. Energy content per unit area decreased even more sharply. In younger farms the energy available is twice than in older farms (>50 years since conversion) ($P < 0.002$);

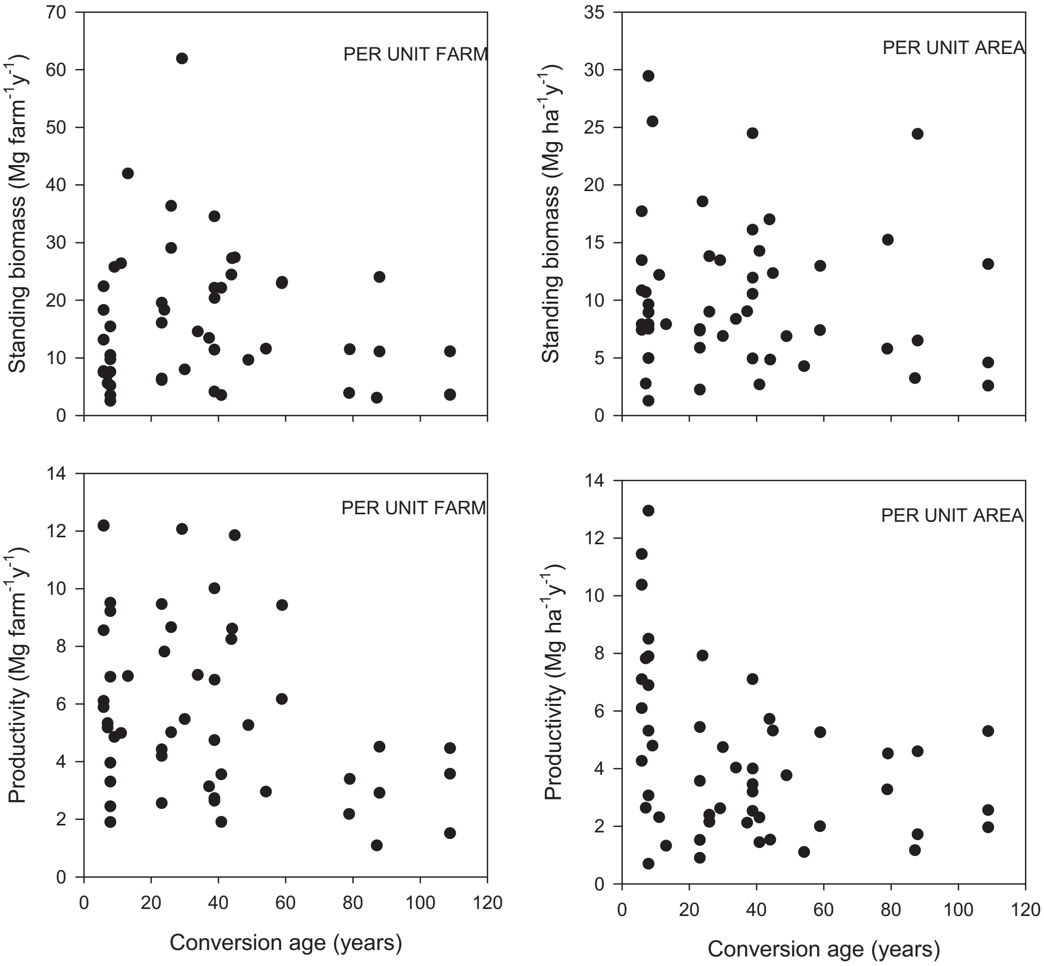

Fig. 1 – **Total available aboveground biomass stocks and productivity usable for pyrolysis with increasing age of conversion on a per farm and hectare basis ($N = 50$).**

within the first 20 years after forest clearing, farms lose approximately 40% energy available for pyrolysis in the farm.

3.5. *Household energy consumption and energy availability for pyrolysis*

Currently all the households in the study use wood as their primary source of cooking energy. Wood energy consumption with traditional stoves ranged from 4.5 to 21.1 GJ y^{-1} $capita^{-1}$ with an average of 10.5 GJ y^{-1} $capita^{-1}$. When comparing wood energy consumption using conventional combustion stoves versus energy available from woody biomass in the farm, none of the households are capable of sustaining their energy consumption. At present households either collect or purchase fuel wood from outside the farm to meet their cooking energy needs. However, if we aggregate other sources of biomass and their available energy for pyrolysis, there is enough biomass in the farming system to sustain household energy consumption using pyrolytic stoves. We also found energy availability per capita to be two-fold higher ($P < 0.026$)

Table 1 – **Total mean aboveground biomass stocks and productivity on a per farm and per area basis for each age conversion category, available as a feedstock and suitable for pyrolysis. Coefficient of variation is shown in brackets; different letters indicate statistically different means or coefficients of variation.**

Conversion	Total standing biomass (Mg $farm^{-1}$ y^{-1})	Total standing biomass (Mg ha^{-1} y^{-1})	Total productivity (Mg $farm^{-1}$ y^{-1})	Total productivity (Mg ha^{-1} y^{-1})
Recent <20	13.5a	10.91a	6.43a	6.09a (83)*a
Intermediate 21-49	19.8a	10.33a	6.17a	3.52a (43)*b
Old >50	11.7a	9.06a	3.82a	3.02a (37)*b

*Main effect significant at $P < 0.0029$.

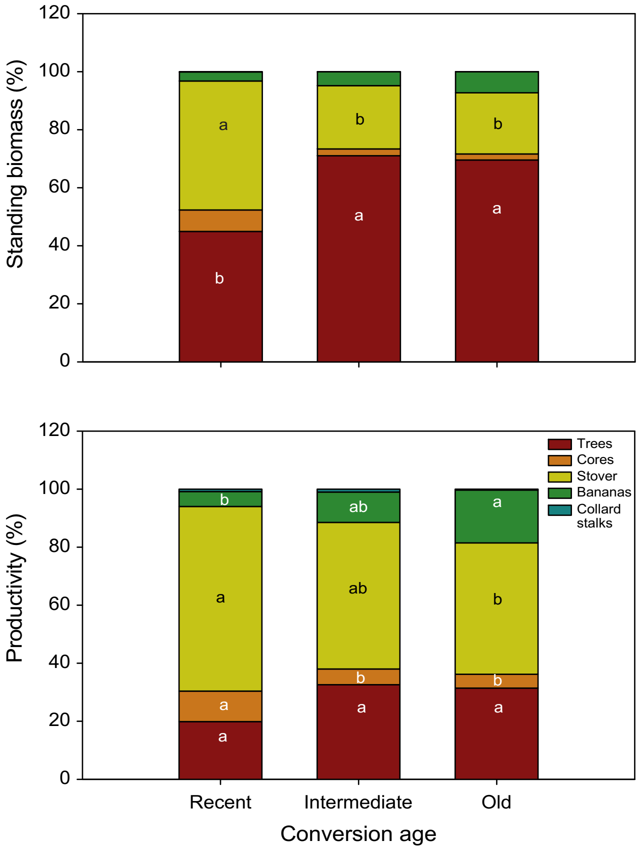

Fig. 2 – Proportion of available total aboveground biomass stocks and productivity from each feedstock considered as sources of fuel for pyrolysis.

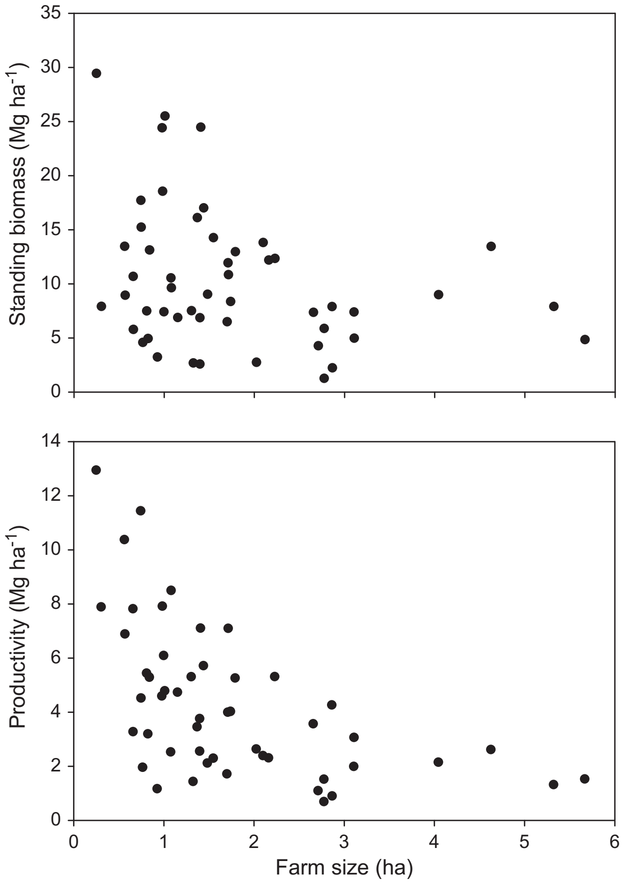

Fig. 3 – Total available aboveground biomass stocks and productivity for all farms with increasing farm size usable for pyrolysis (N = 50).

in younger farms compared to older farms (Table 2). On the other hand, energy consumption per capita was not statistically different across the different conversion age categories.

Energy consumption with a three-stone stove was 46.8 GJ household^{-1} y^{-1}, while the Chepkube stove consumed 52.1 GJ household^{-1} y^{-1} in comparison to 37.4 GJ household^{-1} y^{-1} with the tested pyrolysis stove. The theoretical biochar production from such pyrolytic stoves calculated to 0.46 Mg ha^{-1} y^{-1} (Table 3).

4. Discussion

4.1. *Biomass availability for bioenergy across conversion ages*

The high variability of biomass productivity may be explained by different factors for different age groups of land conversion from forest to agriculture. Biomass productivity in recently converted farms (less than 20 years since conversion from natural forest) showed the greatest variability. These farms were expected to have higher productivity because of their high SOM content [7,20] and greater crop yields [21]. Although on average, recently converted farms have a higher total production of biomass, productivity at the individual farm level can be either low or high. The large variability stems from a complex set of farm characteristics and decisions made by farmers. Biomass productivity in

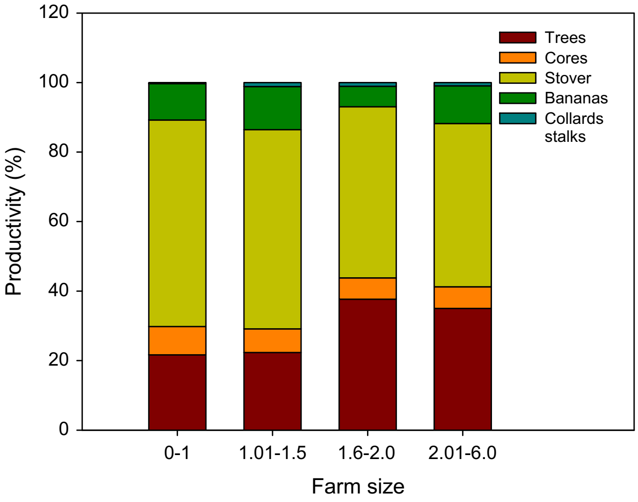

Fig. 4 – Aboveground available biomass productivity usable for pyrolysis for each feedstock with increasing age for all farms.

Table 2 – Total mean available energy for pyrolysis on per farm, per area and per capita basis for each conversion category, available as a feedstock and suitable for pyrolysis. Different letters indicate statistically different means across age conversion categories. Energy contents for different biomass shown in supplementary online Table S3.

Conversion	Energy available for pyrolyis (GJ farm^{-1} y^{-1})	Energy available for pyrolyis (GJ ha^{-1} y^{-1})	Wood energy available for combustion (GJ capita^{-1} y^{-1})	Energy available for pyrolysis (GJ capita^{-1} y^{-1})	Energy consumed (GJ capita^{-1} y^{-1})
Recent <20	100.1a	94.5a	4.58	22.7a	13.0a
Intermediate 21-49	96.1 ab	53.9b	7.33	18.7ab	11.4a
Old >50	55.7b	44.2b	3.86	10.1b	8.4a

these farms is affected by land size and the proportion of land allocated to different resources. Households with smaller farms are constrained by the quantity of land resource, and therefore farmers make decisions based on the most efficient way to use the land [32]. These farms allocate most of the land to crop production, which secures food resources for the household. On the other hand farms with larger land area have a lower need to use their available space in the most efficient way, thus reducing the productivity of total biomass on the farm. The variation in biomass productivity is further evidenced by the variability of farm size in relation to increasing conversion age. Recently converted farms also had a high variability in farm size (Fig. 5), explaining a larger portion of the variation in productivity. Yet, size alone does not explain the variability in biomass production. The types of feedstocks found in the farm also have a large influence. Among the different bioenergy feedstocks maize residues, specifically stover, were the most abundant. The second most productive source of biomass was trees, with a production averaging 1 Mg y^{-1} ha^{-1}. When farmers within different conversion ages allocate land to different types of use, the proportion of land available to them and the type of biomass grown determines the total productivity of the farm. Therefore, variability in productivity within a farm age category is a consequence of both land use management and allocation of resources.

With increasing time since conversion from natural forest, the variability in biomass productivity decreases by 55%. While biomass productivity can be high or low in younger farms for reasons mentioned above, the productive capacity of older farms is always low (Fig. 1). This may be explained both by changes in soil resources and farm size. Several authors [7,20,21] have found that soil organic carbon and productivity decreases with increasing years of conversion from natural forest. Reasons are loss of aggregation through repeated tillage, residue removal and erosion. While the average total biomass productivity for these farms is low, the proportion of productivity from the different types of biomass is also less variable. Older farms tend to redistribute their land allocation among other types of biomass (i.e. trees, bananas), because of the perception of declining land quality [6]. At the same time, land availability is always low with increasing time since forest conversion, whereas both large and small farms existed in newly cleared areas. Therefore, productivity in older conversions is most likely limited by the soil quality and a combination of land availability and type of biomass.

4.2. *Household energy requirement and biomass available for pyrolysis*

The establishment of biochar-bioenergy systems requires the understanding of biomass supply and demand. Wood energy consumption in western Kenya varies between farms. Consumption was greatest in the recently converted farms, while older conversion farms had the lowest wood energy consumption per capita (Table 2). At first glance, this trend is consistent with findings by Hosier et al. [33], who reported rural households in Kenya to use commensurate amounts of wood energy relative to fuel availability. However, wood energy availability within farms is not sufficient to meet energy needs of the households using conventional cook stoves. To explain the higher consumption yet lower supply, of wood energy in younger farms, other factors such as household income or the proximity of households to off-farm sources of wood energy would need to be examined which are beyond the scope of this research.

Currently, agricultural land within the boundaries of the households can provide 48% of the total wood fuel energy needed using traditional combustion stoves in the study area, which means there is a 54% deficit of cooking energy availability in the household. This cooking deficit can be reduced or even matched by introduction of improved combustion stoves. The rocket stove has shown to decrease wood consumption by 62% [11] and the Patsari stove by 64% [34].

In addition, other fuels (straw, other plant materials, twigs, leaf litter, agricultural residues, and dung) are abundant on farms, but require technological improvement to be usable [35]. Pyrolysis stoves have the ability to utilize this additional resource for energy. For smallholder farms, however, biomass is not only a source of fuel but it provides other services in the farm. For example, farmers use biomass as a source of building materials or animal feed. Therefore, taking account of biomass flows for alternate uses is important. After accounting for these uses, the total energy from all sources of biomass was 17.2 GJ capita^{-1} y^{-1} which can supply the remaining 54% of energy needs to meet household cooking requirements. The current production of total biomass energy on the studied farms including non-woody biomass is 9–22% higher than the total cooking energy consumption. Therefore, the current production of biomass energy in the studied farms is also capable of satisfying cooking energy needs if in addition to traditional wood fuel also non-woody biomass can be used. However, the use of on-farm residues for cooking has to be coupled with the return of biochar to the soil. The addition of biochar to the soil may reduce or

Table 3 – Total biomass energy used, wood char residue and biochar energy and total production of biochar for daily cooking tasks on a per household and per capita basis (±SE).

Stove type	N	Total energy used (GJ household^{-1} y^{-1})	Total energy used (GJ capita^{-1} y^{-1})	Total energy wood char residue (GJ household^{-1} y^{-1})	Total wood char residue (Mg household^{-1} y^{-1})	Total biochar produced (Mg household^{-1} y^{-1})	Total energy biochar remaining (GJ household^{-1} y^{-1})	Total biochar produced (Mg ha^{-1} yr^{-1})
Three Stone	9	46.8a ±6.6	7.11ab ± 1.16	7.58a ±0.98	0.28a ±0.05	–	–	–
Chepkube	10	52.1a ±6.2	9.65a ±1.10	9.97a ±0.93	0.38a ±0.05	–	–	–
Pyrolysis	19	37.4a ±4.5	6.69b ± 0.80	3.34b ± 0.67	0.13b ± 0.01	0.52 ± 0.06	11.36 ± 1.42	0.46 ± 0.07

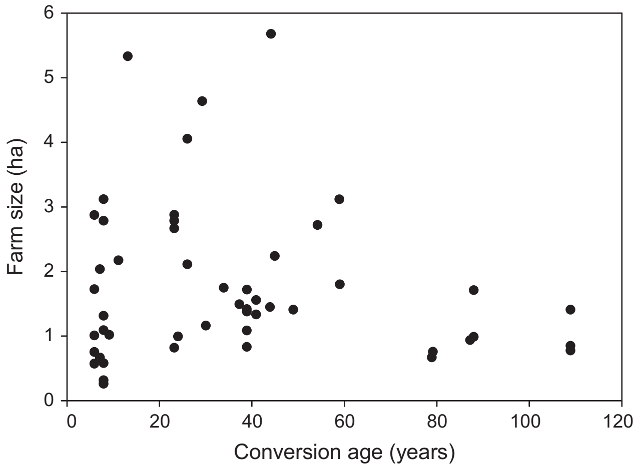

Fig. 5 – Relationship between farm size and conversion age ($N = 50$).

possibly prevent further decrease of soil fertility by providing a source of organic matter which is more recalcitrant [19] and able to improve soil fertility [8,15,16]. Whitman et al. [36] shows that by including biochar returns to soil, SOM may even increase in the same system. Without the return of biochar, the use of crop residues for bioenergy will likely lead to a decline in SOM and fertility [7,21].

However, the total amount of energy available for biochar-bioenergy systems differed significantly across the conversion age categories; younger farms had two-fold greater ($P < 0.05$) amounts of energy available for pyrolysis. This is directly related to the productive capacity of farms, since younger farms currently produce more biomass than older farms. On the other hand, while the availability of biomass energy is larger for younger farms, their energy consumption is also higher. If sustainable harvest and use of biomass is not accomplished in these farms, rapid biomass depletion will lead to future energy shortages.

4.3. *Future implications on energy consumption patterns and crop productivity with the use of a pyrolysis stove*

Our study demonstrates the capacity of smallholder farms to produce sufficient on-farm biomass to sustain current cooking energy needs through pyrolysis or improved cook stoves using combustion. The introduction of a pyrolysis stove will also generate biochar for soil applications. However, the balance between the benefits provided by the biochar additions and the decrease in crop residue return requires further study. Crop residues do not only provide carbon for SOM but also soil protection against erosion, which requires a minimum cover throughout the year [37].

In our study, a household using a traditional three-stone stove or a chepkube stove consumes 7.1 and 9.7 GJ capita^{-1} y^{-1}, respectively. The reason for the failure to reduce biomass energy use with the chepkube stove may have been the lack of standardized construction of the stove leading to incomplete and uncontrolled combustion conditions. In addition, differences in household cooking behavior and housing conditions introduce large variability in energy consumption results [9]. A traditional cook stove studied in Mexico was shown to consume 19.7 GJ capita^{-1} y^{-1}, with significant reductions found for improved cook stoves with 6.5 GJ capita^{-1} y^{-1} [9].

In comparison, the households in our study would consume 6.7 GJ capita^{-1} y^{-1} with the studied pyrolysis stove. Therefore the introduction of the studied pyrolysis stove may lead to a reduction of 27% overall wood energy used. Further, overall energy consumption including biomass used in the pyrolysis chamber was reduced by 7%. MacCarty et al. [11] achieved similar overall wood energy reductions of 47% with stoves built on the principle of gasification; however, the study was carried out under laboratory and controlled conditions. The introduction of a pyrolysis stove to a smallholder farming system, similar to gasification stoves or other improved cook stoves, may lead to gains in energy efficiency [9,34], bearing in mind that improvements in stove designs are needed and may be expected in the near future. Finally it is important to recognize that improved stoves need to be financially accessible to the end users. The introduction of an improved stove can succeed if the return on investment of the stove is rapid. This generally happens in areas where the cost of fuel is already high and wood is scarce [2].

In addition to improved energy efficiencies, the studied pyrolysis stove would produce annually 0.46 Mg ha^{-1} of biochar. This amount of biochar is an order of magnitude less than the biochar application rate of 6 Mg C ha^{-1} studied by Kimetu et al. [8] that led to 26 and 155% crop yield increases with and without nitrogen fertilization, respectively, in highly degraded soils at the same site. However, biochar may be concentrated on a portion of the farm, for example to high-value crops in kitchen gardens. It may be possible that smaller amounts than the ones tested at the studied site [8] may lead to increases in crop productivity as shown in other experiments [16,38].

5. Conclusions

Our study was able to demonstrate the capacity of on-farm biomass production to meet the energy needs of households in western Kenya, if pyrolysis or improved combustion cook stoves are used instead of traditional combustion cook stoves. Variability of biomass production was high but overall, if biomass is harvested and used sustainably, households are able to use different combinations of biomass to meet cooking energy needs through pyrolysis due to the wider range of feedstock types that can be utilized. Not only could overall energy consumption be reduced but women would be less reliant on wood as a source of energy. This may entail significantly less time spent in the collection of wood biomass from other sources and more time for other productive activities. In addition, the production of biochar and its use as a soil conditioner could increase on-farm crop productivity at the amounts produced, resulting in an overall increase in food production for the household. Biochar-bioenergy systems may lead to improvements of smallholder farm livelihoods by addressing several constraints facing resource-poor farmers in Africa. These opportunities would need to be balanced with the removal of crop residues for cooking that would otherwise improve soil protection.

Before wide-spread implementation of biochar-producing cook stoves, significant research efforts must be made to quantify energy output, biochar quantity and quality with different feedstocks available to smallholder farmers and comparing different cook stove designs. We expect significant opportunities in optimization being possible. In addition, research is needed assessing the emissions associated with different designs of pyrolytic cook stoves.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at: doi:10.1016/j.biombioe.2011.05.002.

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