Can biogas digesters help to reduce deforestation in Africa?

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ABSTRACT

Biogas digesters could help to reduce deforestation in Sub-Saharan Africa by providing a source of energy that would otherwise be provided by woodfuel. However, the link between deforestation and use of woodfuel at global level is weak because fuel is often obtained from fallen wood or from sources felled for construction or land clearance. This paper examines the link between deforestation and use of woodfuel, and evaluates whether biogas digesters are likely to help reduce deforestation in Africa. Woodfuel production and consumption in Africa is increasing over time. Of the deforestation observed in 2010, we estimated that 70(±42)% can be attributed to woodfuel demand. Uncertainties in this figure arise from uncertainty in efficiency of energy use in different designs of wood-burning stoves, and the percentage of energy obtained from woodfuel in rural and urban populations. The contribution of woodfuel demand to deforestation is predicted to increase by 2030 to up to 83(±50)%. This is due to an increasing population requiring more woodfuel and so contributing to a higher proportion of total deforestation. Biogas production has the potential to reduce deforestation due to woodfuel demand by between 6-36% in 2010 and between 4-26% in 2030. This is equivalent to 10-40% of total deforestation in 2010, and 9-35% of total deforestation in 2030. The highest contribution to biogas production is likely to be from cattle manure, and the uncertainty in the potential of biogas to reduce deforestation is mainly associated with uncertainties in the amount of biogas produced per animal.

Keywords: Woodfuel; fuelwood, charcoal; deforestation; biogas; Africa

Abbreviations

SSA = Sub-Saharan Africa

GDP = Gross domestic product

1. Introduction

Despite a marked shift in the type of energy use in developing countries from biomass-based fuel to more sophisticated energy delivery, such as gas and electricity [1], the majority of people in developing countries still rely on traditional fuels such as fuelwood, charcoal and dung cakes [2]. In this paper, we define *fuelwood* as the wood that is burnt directly as fuel; and we define *woodfuel* as the sum of the wood used both directly as fuel and indirectly for making charcoal. Historical trends indicate that the use of both fuelwood and charcoal for cooking is increasing [3,4]. Population increase in recent years has contributed to the increased demand for energy, including woodfuel, which is evidenced by collection of woodfuel remaining one of the most important and time consuming household chores in Sub-Saharan Africa (SSA) [5,6]. After the development of the use of fossil fuels and electrical energy, people with high income, mainly living in and around cities, are increasingly attracted towards using these more sophisticated, but expensive, energy types [7]. Charcoal is also very popular and widely used for cooking in most African cities [2,8]. However, for people with low income and living in rural areas, fuelwood is still the primary source of heat energy. In this context, the environmental perspective of woodfuel consumption is one of the areas of interest of this paper.

Different activities and approaches have been used to alleviate the problem of deforestation. In order to reduce over-reliance on woodfuel energy for cooking and heating, alternative sources of energy need to be investigated. Biogas energy could be a suitable alternative for cooking and heating energy and therefore is proposed as one of the approaches to reduce deforestation, particularly deforestation resulting from woodfuel consumption. By providing an alternative energy source that would otherwise be obtained from fuelwood or charcoal, it is widely assumed that biogas digesters could help to reduce the rate of deforestation in SSA [9-12]. However, the link between deforestation and the use of fuelwood and charcoal at global level is weak because fire wood is often obtained from fallen wood or from sources that would already be felled for construction or land clearance [13].

In order to establish the potential impact of biogas on deforestation, the impact of woodfuel demand on deforestation must first be established. Arnold et al. [14] reviewed woodfuel requirements and impacts on forests during the 1980s and found that, globally, there is a very weak link between woodfuel demand and deforestation. However, much has changed since then. The population has increased substantially [15], both the number and size of urban areas has increased [16], and the average gross national income per capita has increased more than threefold [17]. These trends are likely to have modified the 1980 scenario of consumption, demand and choice of fuel. In the developing world, any such changes could have significant effects on forest resources, as woodfuel is the main source of fuel for cooking and heating. It is timely therefore to re-visit the issue of the impact of woodfuel consumption on deforestation.

This paper examines the link between deforestation and the use of fuelwood and charcoal in SSA, and determines whether biogas digesters are likely to help reduce deforestation in Africa. Statistical data have been collated from FAO, UNDP, World Bank and other sources. Some additional data have been obtained from the wider literature. As far as possible, national data have been collected for all countries in SSA. The available data have been used to describe the current situation and to provide future scenarios that have been analysed using the projected figures.

2. Impact of present day energy demand on the forests of Africa

2.1. Amount of wood required to meet present day energy demand

The amount of wood needed to supply current energy demand, W_{dem} (Mt y^{-1}), was calculated from the total energy demand from woodfuel, $E_{\mathrm{dem,wood}}$ (GJ y^{-1}), the gross heat of combustion, $\Delta H_{\mathrm{combustion}}$ (GJ t^{-1}), and the efficiency of energy use, $P_{\mathrm{eff,wood}}$ (energy released / total energy content of the fuel, %);

$$W_{\mathrm{dem}} = \frac{E_{\mathrm{dem,wood}}}{10^2 \times P_{\mathrm{eff,wood}} \times \Delta H_{\mathrm{combustion}}} \qquad [1]$$

The gross heat of combustion, $\Delta H_{\mathrm{combustion}}$, was assumed to be 15.5 GJ t^{-1} after Jensen [18]. The efficiency and design of commonly used stove types in SSA is particularly variable due to limitations in available materials, cultural differences and financial restrictions, so it is difficult to assign an accurate value to the efficiency of energy use ($P_{eff,wood}$). For the five most popular types of stove used, the efficiency for wood burning was measured to be between 14% for an open fire stove [19] and 44% for a rocket stove [20]. Excluding the losses of charcoal production, burning charcoal is more efficient than burning wood. Therefore, for these calculations, $P_{eff,wood}$ is assumed to be 44%. The total national energy demand from woodfuel ($E_{dem,wood}$) was calculated from the energy demand per capita, E_{dem} (GJ caput^{-1} y^{-1}), the population, n_{pop} (caput), and the percentage of the total energy demand that is supplied by woodfuel at national level, P_{wood} (%);

$$E_{dem,wood} = \frac{E_{dem} \times n_{pop} \times P_{wood}}{10^5} \quad [2]$$

This was calculated separately for the urban and rural populations because the energy demand is different in rural and urban areas. The energy demand (E_{dem}) was assumed to be 9.26 GJ caput^{-1} for the rural population, and 6.13 GJ caput^{-1} for the urban population [7,21]. Data for the per capita energy demand in different countries are available from the International Energy Agency Key World Energy Statistics 2012 (data for 2010) [22]. However, numbers are available for less than half of the countries included in the analysis, and the countries with figures given tend to be the richer countries with higher per capita energy demand resulting in an average energy demand across all countries of 32.62 GJ caput^{-1}. Therefore, in order to provide a consistent approach across countries, the more general values provided by Barnes et al [7] were assumed. The size of the urban and rural populations ($n_{pop,urban}$ and $n_{pop,rural}$) was obtained from United Nations, Department of Economic and Social Affairs, Population Division [15]. The percentage of the total energy demand that is supplied by woodfuel (P_{wood}) was calculated for the urban and rural populations assuming that 100% of the rural population and 75% of the urban population use woodfuel for cooking [8];

$$P_{wood} = \frac{\left(n_{pop,rural} + \left(0.75 \times n_{pop,urban}\right)\right)}{\left(n_{pop,urban} + n_{pop,rural}\right)} \quad [3]$$

This assumption is not likely to hold for countries with a high Gross Domestic Product (GDP) as householders move up the energy ladder and switch to cleaner and more convenient sources of energy. Therefore countries with a GDP over 10 k$ caput^{-1} were excluded from subsequent calculations. Although inequalities in the distribution of wealth may mean that a significant proportion of the population will not be able to move up the energy ladder and will still mainly rely on woodfuel, if sufficient wealth is in a country, even lower sections of the population will begin to benefit. The high correlations obtained in later calculations justified the choice of 10 k$ caput^{-1} as the cutoff point. This cutoff excludes Botswana, Equatorial Guinea, Gabon, Libyan Arab Jamahiriya, Mauritius, Seychelles and South Africa.

2.2. Comparison of woodfuel demand and woodfuel production in Africa 1961-2009

In this paper, we have defined woodfuel *production* as the amount of wood extracted for fuel from forests and plantations and processed commercially. However, much woodfuel is collected informally and is never recorded, so the values calculated for *consumption* of woodfuel may well be significantly higher than *production* figures. The information from the Global Forestry Resources Assessment, FAOSTAT, and Human Development Report has been used to examine production in this section [23-25]. Note that for most countries, these numbers are based on FAO estimates using an assumption of average woodfuel use per inhabitant, so are also subject to error. However, these values are used here merely to ground truth our estimates of present day woodfuel demand. It is important to do this as Eqn.1 will later be used to determine the potential impact of biogas production on wood fuel demand.

Country-wise figures for fuelwood and charcoal production were obtained from FAO ForesSTAT (2010, 2011). These figures are provided by the different countries through an annual survey conducted by the FAO Forestry Department together with the International Tropical Timber Organization (ITTO), the Statistical Office of the European Communities (Eurostat), and the UN Economic Commission for Europe (UNECE). Where countries have not provided information through this survey, estimates of annual production are made by FAO based on trade journal reports, statistical yearbooks or other sources. If these data are unavailable, historical figures are repeated until new information is found.

The original volume-based data (V_{wood}, m^3) were converted to weights (Y_{wood}, t) using the wood density factor given by FAO [26], $D_{wood} = 0.75$ t m^{-3}:

$$Y_{wood} = D_{wood} \times V_{wood} \qquad [4]$$

In 1961, fuelwood production in Africa was 157 Mt (Fig.1), reaching 448 Mt in 2009 [24], an increase of 185% (291 Mt) over a nearly 50 year time span. Out of 57 countries studied, production was increased in 46 countries by 0-75 Mt (8-1452%) within this duration (Table 1). A decrease within this period was observed in six countries ranging from 0 to 1 Mt (33-98%), except in the case of Morocco, where the decrease was much greater than the other countries in the study (4 Mt, i.e. 95%).

Charcoal production in the same 50 year period followed a very similar trend but with a different scale (Fig. 1). In 1961, charcoal production in Africa accounted for 5 Mt, and steadily increased to 29 Mt in 2009, an increase of 534% from the 1961 value (Table 1). The magnitude of increase in charcoal production was much higher than fuelwood production (Fig. 2), indicating that charcoal is gaining in popularity over fuelwood in Africa. Charcoal production increased in 50 countries by 0-4 Mt (75-2290%).

INSERT TABLE 1 AND FIG. 1 & 2 HERE

The higher rate of increase of charcoal production compared to fuelwood can be attributed to the increasing rate of urbanisation in SSA [2]. Compared to fuelwood, charcoal is more popular amongst city dwellers and is the main source of cooking energy in most African cities [27,28]. It is estimated that over 50% of people in Africa will live in cities by 2050 [15]. As a result, the use of charcoal is increasing at an increasing rate, but at the same time the rate of increase of fuelwood use has started to decline [29]. Therefore future demand for charcoal is expected to increase even further. Because burning charcoal is less efficient than direct burning of wood, requiring 4-6 times more wood to release the same amount of energy [28], increased charcoal use will further increase the amount of wood required for fuel.

Woodfuel was calculated as that required to produce charcoal plus that used directly for fuelwood. The amount of woodfuel required to produce one unit of charcoal, known as the woodfuel to charcoal conversion ratio (R_{WC}), is dependent on the moisture content of the wood. For green wood, the ratio was given by FAO [26] as 7:1, whereas for oven dried wood the ratio was only 5:1. There is variation in the conversion ratio provided by different published reports. Amous [30] reported the conversion ratio to be 4.5:1, while Mercer et al. [8] reported it to be 8-12:1. We assume use of freshly cut green wood for charcoal making is the general trend, and therefore, in this study we used the FAO conversion factor for green wood, $R_{WC} = 7$. The correlation between national level total woodfuel production and deforestation rates was also significant ($r^2 = 0.4$; $p < 0.01$; df = 51).

As illustrated in Fig. 3, across countries with a GDP below 10 k\$ caput^{-1}, there is a highly significant correlation between the woodfuel demand (W_{dem}) and the woodfuel production ($R^2 = 0.6$; $p < 0.01$; df = 40). Given that woodfuel production includes export of woodfuel, a factor that is not accounted for in these calculations, and neglects some non-commercial collection of woodfuel, this suggests that the calculation of woodfuel demand from the energy demand is providing a reasonable estimate of woodfuel use.

INSERT FIG. 3 HERE

2.3. Present day rate of deforestation

Deforestation is driven by a number of different factors including extraction of wood by humans, the occurrence of wildfires, and loss of trees due to disease. Assuming non-human factors remain constant, we might expect there to be a relationship between the total wood extracted from forests and deforestation. Not all of the woodfuel demand is obtained from forests; woodfuel can also be obtained from plantations, recycled wood from buildings and from other sources. The percentage of the woodfuel demand that is provided by forests, P_F, can be calculated from FAO figures, and the total wood extracted from forests for woodfuel will be this percentage less than the total woodfuel demand. Wood is also extracted from forests for a number of different reasons, in addition to woodfuel demand, including construction and agricultural expansion. The percentage of the wood extracted from forests that is used to satisfy woodfuel demand, P_{fuel}, can be calculated from FAO figures; the total wood extracted from forests can then be estimated from the woodfuel demand by dividing by this percentage. Therefore, the amount of wood required to meet the woodfuel demand was translated into the total amount of wood extracted from forests, $W_{ext,F}$ (Mt y^{-1}) using 2005 FAO figures for the percentage of woodfuel that is extracted from forests, P_F, and the percentage of the wood extracted that is for fuel, P_{fuel} (sheet 13, [23]),

$$W_{ext,F} = \frac{P_F \times W_{dem}}{P_{fuel}} \quad [5]$$

The total area of deforestation is expected to be dependent on the regeneration of wood in forests (calculated from the net primary production and the area of forest), the extraction of wood from forests ($W_{ext,F}$) and the losses of wood due to forest fires, insects, diseases, and other biotic and abiotic factors. Data on the area of forests and losses of wood were obtained from FAO [23]. Data on the net primary production were obtained from the Integrated Model to Assess the Environment (IMAGE) version 2.4 [31]. Dividing by national figures for the density of wood in forests (t ha^{-1}) [23] converts the mass of wood deforested (t y^{-1}) into the area of deforestation (ha). However, deforestation calculated by this approach was not significantly correlated to the FAO [23] observed area of deforestation for 2010 ($R^2 = 0.04$; $p = 0.1$; df = 51). This was perhaps due to non-uniform density of wood in forests and preferential collection of wood from forest margins. Attempts to account for the collection of wood from forest margins made a distinction between the area that is forest (over 10% tree cover; [23]) and the wooded areas that are not classified as forest. The wood demand was then assumed to be extracted preferentially from the non-forest area before drawing on the forested areas. However, this did not significantly improve the correlation between the observed and calculated deforestation. Therefore, this approach was abandoned.

By contrast, after excluding the countries suffering high forest losses due to forest fires and other biotic and abiotic factors [23], Fig. 4 illustrates that the wood extracted from forests ($W_{ext,F}$) is highly significantly correlated to the observed area of deforestation ($R^2 = 0.8$; $p < 0.01$; df = 24). The data was divided in half to allow a linear regression equation to be fitted between the observed area of deforestation and the woodfuel demand from forests for half of the data, and then independently evaluated against the other half. This was achieved by ordering countries alphabetically, and selecting the first half of the countries for development of the equation and the second half for evaluation. The equation obtained for the area deforested, A_{def} (km^2 y^{-1}) by linear regression was

$$A_{def} = \left(-21.2 \times W_{ext,F}\right) - 82 \quad [6]$$

Even using only half of the data, the correlation between A_{def} and $W_{ext,F}$ was highly significant ($R^2 = 0.7$; $p < 0.01$; $n = 15$). This equation was used to calculate the area deforested in the remaining countries and achieved a highly significant correlation between the observed and calculated areas of deforestation as shown in Fig. 5 ($R^2 = 0.8$; $p < 0.01$; df = 13) with a root mean squared error [32] of 54%. Note that this correlation does not imply causality between woodfuel demand and deforestation. However, it does provide us with an equation that can be used to determine the likely impact of changing woodfuel demand, for instance by increasing the number of biogas digesters available, on the area of deforestation.

INSERT FIG. 4 & 5 HERE

2.4. Deforestation due to present day woodfuel demand

In the previous section, the area of deforestation was calculated from the wood extracted from forests. This can be used to calculate the area of deforestation that can be attributed to woodfuel demand alone by subtracting the area of wood extracted for uses other than woodfuel from the total area of deforestation. The wood extracted from forests for uses other than woodfuel, $W_{ext,F,notfuel}$ (Mt y^{-1}), was calculated by subtracting the woodfuel demand from forests ($W_{dem,F}$) from the total wood extracted from forests ($W_{ext,F}$),

$$W_{\mathrm{ext,F,notfuel}} = W_{\mathrm{ext,F}} - W_{\mathrm{dem,F}} \quad [7]$$

For the countries with GDP < 10 k$ caput^{-1} and with no significant losses due to forest fire and other biotic and abiotic processes, this was then used to calculate the area of deforestation due to factors other than woodfuel, $A_{\mathrm{F,notfuel}}$ (km^2 y^{-1}) using Eqn.6. The area of deforestation due to woodfuel demand, $A_{\mathrm{def,fuel}}$ (km^2 y^{-1}) was then obtained by difference.

The data was ordered alphabetically and the first half of the data was selected for development of the linear regression between the area of deforestation due to woodfuel demand and the wood extracted from forests for fuel (Fig. 6; $R^2 = 0.98$; $p < 0.01$; df = 13)

$$A_{\mathrm{def,fuel}} = -18.5 \times 10^{8} \times W_{\mathrm{ext,F}} \quad [8]$$

When Eqn.8 was used to estimate the area of deforestation due to woodfuel demand across the remaining countries, as expected, because the fitted Eqn.6 was used in the calculation, there was a highly significant correlation between the calculated and the observed values ($R^2 = 0.98$; $p < 0.01$; df = 13), with a root mean squared error [32] of 6%. This error is added to the error in the estimated deforestation due to total wood extraction (54%) to give the total average error in estimated deforestation due to woodfuel extraction (60%).

INSERT FIG. 6 HERE

Having used the countries with no losses due to forest fire, or other biotic or abiotic factors to separate out the area of deforestation due to woodfuel extraction from the other causes of deforestation, the new equation can be used to calculate the area of deforestation due to woodfuel extraction for all countries, excluding those with a GDP above 10 k$ caput^{-1} for which the assumptions about the proportion of energy supplied by fuelwood or charcoal are not likely to hold. This then gives us a method to calculate the deforestation due to woodfuel demand across Africa, even in countries with high wood losses from forests due to other factors. The average deforestation due to woodfuel demand is estimated by Eqn.8 to be 520 (± 310) km^2 y^{-1}, with a maximum value of 3340 (± 2000) km^2 y^{-1} in Nigeria. The total deforestation due to woodfuel over the 46 countries considered is estimated to be 24,030 (± 14,390) km^2 y^{-1}, which amounts to 70 (± 42) % of the total deforestation observed.

3. Impact of future energy demand on the forests of Africa

3.1. Projected trends in woodfuel consumption

Broadhead et al [3] developed models to attempt to predict fuelwood and charcoal consumption based on a number of variables, which included total population, total GDP, GDP per capita, degree of urbanisation, oil price, oil production, total forest area, forest cover, forest area per capita, total land area, land area per capita, temperature, rainfall and Human Development Index (HDI). Authentic country-wise figures for future woodfuel production are lacking. Therefore Broadhead's estimates of consumption have been used here to check the validity of our calculations of woodfuel demand. Future estimates of consumption were obtained using data from FAO studies and the Human Development Report [3,25].

As illustrated in Fig. 7, consumption of fuelwood in Africa increased by 86% over the 40 year period between 1970 and 2010 (261 Mt in 1970 cf 486 Mt in 2010). According to the past trend, fuelwood consumption is expected to reach 545 Mt in 2030, which is 109% more than the amount consumed in 1970 [3]. Projected figures based on the past trend suggest that the increase in the fuelwood consumption will slow down in future. The annual increase in the consumption of fuelwood was 3.7 Mt y^{-1} during 1970-75, which rose to 4.5 Mt y^{-1} during 2005-10, but this increasing trend is expected to reverse during 2025-30 with a small negative annual increment (-0.3 Mt y^{-1}).

During the same period, charcoal consumption increased significantly (8 Mt in 1970 cf 30 Mt in 2010), an increase of 274% compared to the 86% increase in woodfuel (Fig. 7). By 2030, the rate of charcoal consumption in Africa is expected to reach 46 Mt, which is 470% more than consumption in 1970 and 52% more than in 2010. During 1970-2030, the annual consumption of charcoal is predicted to increase at the rate of 0.6 Mt y^{-1}. The rate of increase is also increasing over this period. Between

1970-75, charcoal consumption increased at the rate of 0.3 Mt y^{-1} which rose to 0.8 Mt y^{-1} between 2005-10 and is expected to decline to 0.6 Mt y^{-1} in 2025-30. Thus the percentage of woodfuel consumed as charcoal is increasing over the years (Table 2). Increasing use of less efficient energy (charcoal) will increase the demand and this is likely to drive increased cutting and collection of wood for fuel [28].

INSERT TABLE 2 AND FIG. 7 HERE

The average consumption of total woodfuel by African countries increased by 7 Mt during the last 40 years (6 Mt in 1970 cf 13 Mt in 2010). Projected figures indicate that the future consumption is expected to increase by 3 Mt per country in the next 20 years (i.e. 16 Mt in 2030). The rate of increase in total woodfuel consumption is, however, slowing down; it was increasing at a rate of 0.2 Mt $year^{-1}$ per country during 1970-2010 while it is expected to be 0.1 Mt $year^{-1}$ per country during 2010-2030. In comparison to 2010, the consumption in 2030 will decrease by 0.7 Mt (0-2 Mt) in four countries (Morocco, Réunion, South Africa and Tunisia), while it will remain unchanged in two countries (Botswana and Seychelles).

3.2. Amount of wood required to meet future energy demand

The woodfuel demand (W_{dem}) in 2030 was calculated using Eqn.2-4, given the rural and urban populations (n_{pop}) provided by United Nations, Department of Economic and Social Affairs, Population Division (2012) and assuming the rural and urban energy demand (E_{dem}) remain at 9.26 GJ $caput^{-1}$ for the rural population [21], and 6.13 GJ $caput^{-1}$ for the urban population [7]. The percentage of the total energy demand that is supplied by woodfuel (P_{wood}) was assumed to remain at 100% for the rural population and 75% for the urban population [8]. The efficiency of cook stoves ($P_{eff,wood}$) was assumed to remain at 44%. Improvements in the availability of technology in SSA are likely to change these percentages, but these assumptions were used here in order to calculate a business-as-usual scenario. The gross heat of combustion, $\Delta H_{combustion}$, was again assumed to be 15.5 GJ t^{-1} after [18].

Using this business-as-usual scenario, the woodfuel consumption calculated by Broadhead et al. [3] was significantly correlated to the calculated woodfuel demand (R^2 =0.3; $p < 0.01$; n = 42), with close correspondence between the linear regression and the 1:1 line (Fig. 8). This provides confidence in the use of Eqn.2-4 to estimate woodfuel demand in 2030.

INSERT FIG. 8 HERE

3.3. Future area of deforestation

The area of deforestation (A_{def}) was calculated using Eqn.5-6, assuming the percentage of woodfuel that is extracted from forests (P_F) and the percentage of the wood extracted that is used for fuel (P_{fuel}) remain in 2030 as given for 2005 by FAO [23]. Given depletion in forest area and advances in technology, the pattern of extraction and fuel use is likely to have significantly changed by 2030. However, these percentages were again used in the absence of better data to provide a calculation for business-as-usual.

The "observed" area of deforestation was obtained from the 25 year average of FAO [23] estimates for deforestation between 2005 and 2030. Fig. 9 shows the rate of change in forest area calculated using Eqn.6 compared to the area of deforestation estimated from the FAO data, again excluding countries with high losses due to fire and other biotic or abiotic factors and GDP > 10 k$ $caput^{-1}$. Countries showing net afforestation were also excluded as these lie outside the bounds of the equation, which is designed to predict deforestation. The calculated and the observed areas of deforestation are highly significantly correlated (R^2 = 0.6; $p < 0.01$; n = 24). The root mean squared error [32] is high (110%); this high error can be attributed to the evaluation of one model against another, but the high correlation again adds confidence in the use of this approach to estimate future areas of deforestation.

INSERT FIG. 9 HERE

3.4. Future deforestation due to woodfuel demand

The deforestation due to woodfuel demand in 2030 was calculated using Eqn.8 for all countries, excluding countries with GDP > 10 k$ caput^{-1} and showing net afforestation, which are outside the bounds of the equation. The average deforestation due to woodfuel demand is estimated by Eqn.8 to be 910 (± 550) km^2 y^{-1}, an increase of 75% over the present day value. The maximum deforestation is estimated to be 5030 (± 3020) km^2 y^{-1}, again in Nigeria. The total deforestation due to woodfuel demand over the 46 countries considered is estimated to be 41,950 (± 20,220) km^2 y^{-1}, which has increased to 83 (± 50) % of the total deforestation observed from the present day value of 70 (± 42) %. This is consistent with an increasing population, requiring more woodfuel and so contributing to a higher proportion of the total deforestation.

4. Possible impact of biogas on deforestation

4.1. Potential biogas production

The main feedstocks used in biogas production in SSA are cow and pig manure. Some use is also made of plant wastes, other animal manures and human faecal materials [33], but this is less widespread than using cow and pig manure. Therefore, the national potential for biogas production was estimated from the number of cows and pigs. The potential of human faeces to be used to boost the biogas production, by attaching a pit latrine to the digester, was also considered.

The amount of biogas produced per animal depends on the type of animal, the food intake, the size and the breed. Orskov et al. [34] estimated that manure of housed dairy and beef cattle can produce over 2 m^3 day^{-1} per head, whereas manure from feedlot beef can produce as little as 0.3 m^3 day^{-1} per head, pork pigs less than 0.2 m^3 day^{-1} per head and human faeces 0.02 m^3 day^{-1} caput^{-1}. Heegde and Sonder [35] suggest that 25 kg of cow dung produce 0.8-1.0 m^3 of biogas, which, accounting for losses during grazing, is produced by 3-4 cows each day. This suggests that cows produce less than ((1 m^3 / 25 kg dung) x (25 kg day^{-1} dung / 3 cows)) = 0.3 m^3 day^{-1} per head. Therefore, in the subsequent calculations, it is assumed that the amount of biogas produced by cow manure ($V_{biogas,cow}$) is between 0.3 and 2 m^3 day^{-1} per head, by pig manure ($V_{biogas,pig}$) is 0.2 m^3 day^{-1} per head, and by human faeces ($V_{biogas,human}$ is 0.02 m^3 day^{-1} caput^{-1},

$$V_{\text{biogas}} = 365 \times \left(\left(V_{\text{biogas,cow}} \times n_{\text{cows}} \right) + \left(V_{\text{biogas,pig}} \times n_{\text{pigs}} \right) + \left(V_{\text{biogas,human}} \times n_{\text{pop}} \right) \right) \qquad [9]$$

where V_{biogas} is the volume of biogas produced (m^3 y^{-1}), n_{cows} is the number of cows, n_{pigs} is the number of pigs, and n_{pop} is the human population.

4.2. Potential replacement of woodfuel by biogas

The potential national energy production by biogas, E_{biogas} (GJ year^{-1}), can be calculated from the volume of biogas produced, V_{biogas} (m^3 y^{-1}) and the energy available in the biogas, c_{biogas} (0.216 GJ m^{-3} biogas [36]),

$$E_{\text{biogas}} = V_{\text{biogas}} \times c_{\text{biogas}} \qquad [10]$$

The energy demand from wood that could be replaced by biogas, $E_{dem,biogas}$ (GJ y^{-1}), is determined by the typical efficiency of biogas stoves, $P_{eff,biogas}$ (%),

$$E_{\text{dem,biogas}} = \frac{E_{\text{biogas}} \times P_{\text{eff,biogas}}}{100} \qquad [11]$$

Khandelwal et al [37] define 55% efficiency as the minimum required efficiency for a biogas stoves. Therefore, $P_{eff,biogas}$ was set to 55%. This compares to a maximum efficiency for wood burning stoves of $P_{eff,wood}$ = 44% [20].

The potential for reduction in woodfuel demand achieved by replacing woodfuel with biogas, $W_{dem,biogas}$ (t y^{-1}), is then obtained by substituting $E_{dem,biogas}$ into Eqn.1,

$$W_{\text{dem,biogas}} = \frac{10^4 \times E_{\text{dem,biogas}}}{P_{\text{eff,wood}} \times \Delta H_{\text{combustion}}} \qquad [12]$$

National statistics for the number of cows and pigs per country were obtained for 2010 from FAOStat (production) [38]. Statistics for the human population were obtained for 2010 from UNDP [25]. The largest potential for production of biogas is from cow manure (Fig. 10), potentially reducing the average energy demand from woodfuel by 6% (if $V_{\text{biogas,cow}}$ = 0.3 m^3 day^{-1} per head) or 36% (if $V_{\text{biogas,cow}}$ = 2 m^3 day^{-1} per head). Depending on the volume of biogas produced per head, the reduction in energy demand due to biogas production from cow manure ranges from 0 – 1% in Mauritius to 27 - 180% in Botswana. Percentages over 100% indicate that there is potential to provide more biogas than is needed for cooking, the excess being used for other activities, such as lighting. Including pig manure increases the potential reduction by 0% (in a number of countries where no pigs are recorded) to 6% (in Cape Verde), and including human faeces increases the potential reduction by 1% (in most countries) to 2% (in Djibouti, Gabon and Libyan Arab Jamahiriya). This is equivalent to an average reduction in woodfuel demand of 1 to 8 Mt y^{-1}, which would reduce current deforestation by an average of 30 - 150 km^2 y^{-1} (5 - 23% of current deforestation), with a total reduction over the 46 countries included in the analysis of 1380 - 7120 km^2 y^{-1}.

INSERT FIG. 10 HERE

4.3. Future impact

Assuming the population of cattle and pigs remains at the 2010 level, biogas production will have a reduced impact on deforestation in the future as the energy demand increases in line with the increase in population. By 2030, biogas production will have the potential to reduce the average energy demand by between 4% (if $V_{\text{biogas,cow}}$ = 0.3 m^3 day^{-1} per head) and 26% (if $V_{\text{biogas,cow}}$ = 2 m^3 day^{-1} per head). If the population of cattle and pigs continues to increase in SSA by 1.5% y^{-1} and 3% y^{-1} respectively, as recorded by FAO between 1980 and 2007 [39], then the potential reduction in energy demand provided by biogas will increase to between 6% (if $V_{\text{biogas,cow}}$ = 0.3 m^3 day^{-1} per head) and 35% (if $V_{\text{biogas,cow}}$ = 2 m^3 day^{-1} per head).

5. Conclusions

A key conclusion from the above calculation is that 70 (± 42) % of the deforestation observed in many African countries can be attributed to woodfuel demand. This is in contrast to the conclusions of Arnold et al. [14], which suggest that globally, woodfuel demand is not a major cause of deforestation. The difference in our conclusions can be attributed in part to the focus in this study on Africa, as well as the removal from the analysis of countries with very high losses due to factors other than woodfuel demand and countries with a high GDP, which were clouding the relationship between wood demand from forests and deforestation. Having removed these countries from the analysis, a significant correlation between wood demand from forests and deforestation could be established, allowing the relationship between woodfuel demand and deforestation to be developed and then extended to all countries with a GDP per capita below 10 k$. Uncertainties in this conclusion arise from uncertainty in the efficiency of energy use in the different designs of wood burning stoves used in Africa, the percentage of the woodfuel requirement that is actually supplied and the percentage of energy obtained from woodfuel in the rural and urban populations.

The contribution of woodfuel demand to deforestation is predicted to increase by 2030 to 83 (± 50) %. This is consistent with an increasing population, requiring more woodfuel and so contributing to a higher proportion of the total deforestation. This was calculated for the business-as-usual scenario, assuming the pattern of rural and urban energy demand, efficiency of cook stoves and percentage of woodfuel extracted from forests remains unchanged. In future, developments in infrastructure, at least in the urban environment, are likely to reduce the percentage of energy demand obtained from woodfuel; this may reduce the overall woodfuel demand. However, charcoal is more popular and widely used in urban areas. The speed of urbanisation is rapid in Africa and 50% of African people are projected to live in cities by 2050 [2]. Energy provision by charcoal is 4-6 times less efficient than by wood, and so charcoal use in such large urban areas is likely to counter the reduction in woodfuel demand due to infrastructure advances; energy use per capita may also increase with demographic changes. Efficiency of cook stoves is likely to improve with technological developments; this would reduce the woodfuel demand. In addition, the percentage of woodfuel extracted from forests is likely to be reduced as accessible forest areas decline. All these factors will reduce the contribution of woodfuel demand to deforestation, so the woodfuel contribution to deforestation of 83% should be assumed to be a high estimate.

The final key conclusion is that biogas production has the potential to reduce deforestation due to woodfuel demand by 6-36% in 2010 and by 4-26% in 2030. The highest contribution to biogas production is from cattle manure. The main uncertainty in this conclusion is in the amount of biogas produced per cow. This is highly dependent on the type of animal, the food intake, the size and the breed, and is estimated to be between 0.3 and 2 m^3 biogas day^{-1} per head [34]. More accurate estimates of the biogas produced from the manure of cows in the different countries of Africa would greatly reduce the uncertainty in these calculations.

Woodfuel production and consumption in Africa is increasing over time and expected to increase in the future. The current trend of woodfuel production and consumption is not sustainable in the longer term. Greenhouse gas emissions may increase if woodfuel consumption is reduced without providing a green energy option to the users. Biogas is a suitable green-energy option, which has potential to reduce present day deforestation by up to (36 x (70 $\pm$ 42)) = 10-40%, and future deforestation by up to (26 x (83 $\pm$ 50)) = 9-35%. Therefore, any reduction in woodfuel consumption achieved as a result of biogas production is expected to have favourable effect on reducing deforestation.

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Tables

Table 1 - Woodfuel production in Africa, 1961-2009.

Table 2 - Amount of fuelwood and charcoal consumed in Africa

Table 1 - Production of fuelwood and charcoal in Africa, 1961-2009

Countries	Fuelwood production (kt)			Charcoal production (kt)		
	1961	2009	Increase	1961	2009	Increase
Algeria	2124	6054	3930	149	669	520
Angola	838	2938	2100	36	283	247
Benin	3668	4671	1003	43	235	192
Botswana	430	509	78	18	71	53
Burkina Faso	4526	9450	4924	155	570	415
Burundi	2636	6833	4197	105	303	198
Cameroon	5062	7364	2302	88	419	332
Cape Verde	61	1	-60	9	1	-8
Central African Republic	1163	1500	338		186	186
Chad	1969	5212	3243	87	393	305
Comoros	33	194	162	6	39	33
Congo	620	986	367	0	4	4
Côte d'Ivoire	4685	6667	1981	68	459	391
DR Congo	13651	56585	42934	279	1956	1678
Djibouti	0	262	262	2	47	45
Egypt	7534	13047	5514	766	1344	577
Equatorial Guinea	229	143	-86	3	9	6
Eritrea	0	1954	1954		179	179
Ethiopia	0	74903	74903		3644	3644
Gabon	268	803	534	3	20	16
Gambia	157	513	357	11	58	47
Ghana	4715	27423	22708	102	1537	1435
Guinea	6554	8926	2373	94	341	246
Guinea-Bissau	293	317	24	12	63	51
Kenya	6259	18619	12360	88	902	814
Lesotho	1106	1563	457	37	95	58
Liberia	1170	5063	3893	25	225	201
Libyan Arab Jamahiriya	218	704	487	5	103	98
Madagascar	1633	9825	8192	0	1068	1068
Malawi	2404	4011	1607	127	478	351
Mali	1903	3948	2045	28	129	101
Mauritania	499	1343	844	22	180	158
Mauritius	32	5	-27		26	26
Morocco	3973	200	-3773	25	105	79
Mozambique	4965	12543	7578	0	1867	1867
Namibia	253	612	360	12	57	45
Niger	1621	2143	522	77	569	491
Nigeria	27178	47095	19917	771	3850	3079
Réunion	88	23	-65	23	15	-8
Rwanda	2078	1399	-679	86	265	179
Sao Tome and Principe	35	80	45	2	9	7
Senegal	2181	4047	1867	110	110	0
Sierra Leone	-	-	-	81	373	292
Somalia	1975	9123	7147	179	934	754
South Africa	580	9000	8420		703	703
Sudan	7180	13911	6730	213	995	782
Swaziland	0	784	784	7	41	34
Togo	2609	3318	709	43	222	179
Tunisia	964	1633	669	90	212	122
Uganda	10487	29285	18798	187	907	719
Tanzania	9035	16941	7906	263	1558	1295
Zambia	2475	6734	4259	95	568	473
Zimbabwe	2963	6469	3507	1	11	10
Total (kt)	**157,073**	**447,673**	**290,600**	**4,634**	**29,403**	**24,769**

(Data source: [24])

Table 2 - Amount of fuelwood and charcoal consumed in Africa

Year	Fuelwood[a] (kt)	Charcoal[a] (kt)	Charcoal as woodfuel[b] (kt)	Charcoal as wood[c] (%)
1970	261,072	8,091	56,637	21.7
2010	485,663	30,254	211,778	43.6
2030	544,817	46,114	322,798	59.3

[a] = Data source: [3]
[b] = Amount of woodfuel required to make given amount of charcoal. Calculated using the conversion factor proposed by FAO [26], as: Woodfuel = Charcoal x 7.
[c] = Amount of woodfuel required to make given amount of charcoal as percentage of woodfuel consumed. Calculated as; % woodfuel consumed as charcoal = (Woodfuel consumed as charcoal/ Woodfuel consumed) x 100

Figures

Fig. 1 - Fuelwood and charcoal production in Africa 1961-2009 (Data source: [24]). Note different axes for fuelwood and charcoal.

Fig. 2 - Percent change (in comparison to 1961) in fuelwood and charcoal production in Africa during 1961-2009.

Fig. 3 - Comparison of woodfuel production extrapolated from FAO [23] and the calculated woodfuel demand assuming 62% efficiency of energy use. Plot shows the 1:1 line (dotted line) and the linear regression between production and woodfuel demand (solid line).

Fig. 4 - Relationship between the observed area of deforestation [23] and the calculated wood extracted from forests.

Fig. 5 - Independent evaluation of calculated and observed area of deforestation.

Fig. 6 - Separation of area of deforestation [23] into deforestation due to woodfuel demand ($A_{def,fuel}$) and deforestation due to other factors.

Fig. 7 - Trend of fuel wood (top) and charcoal (bottom) consumption and population in Africa, 1970-2030. (Data source: [3,25]).

Fig. 8 - Comparison of woodfuel consumption, provided by Broadhead [3] and the calculated woodfuel demand assuming 62% efficiency of energy use. Plot shows the 1:1 line (dotted line) and the linear regression between production and woodfuel demand (solid line).

Fig. 9 - Rate of change in forest area in 2030, calculated using Eqn.6 compared to the area of deforestation estimated from the FAO data [23], excluding countries with high losses due to fire and other biotic or abiotic factors and GDP > 10 k$ caput^{-1}.

Fig. 10 - Potential reduction in energy demand from woodfuel using cattle and pig manure and human faeces to produce biogas. Biogas production per head is assumed for cattle to be 0.3 m^3 day^{-1} [35], for pigs to be 0.2 m^3 day^{-1} [34], and for human faeces to be 0.02 m^3 day^{-1} [34]. Note, the rate of biogas production from dairy cattle [34] is likely to be higher than this assumption.

Fig. 1

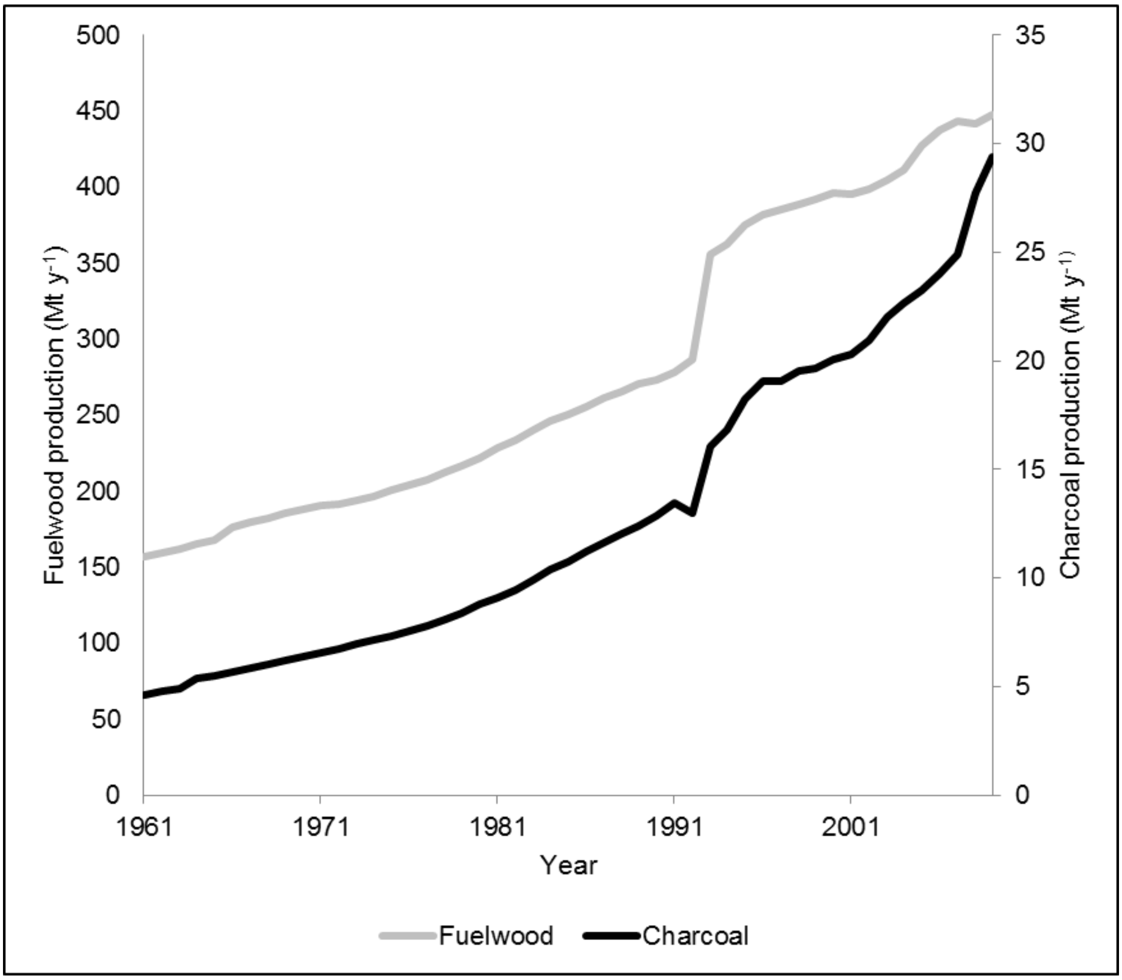
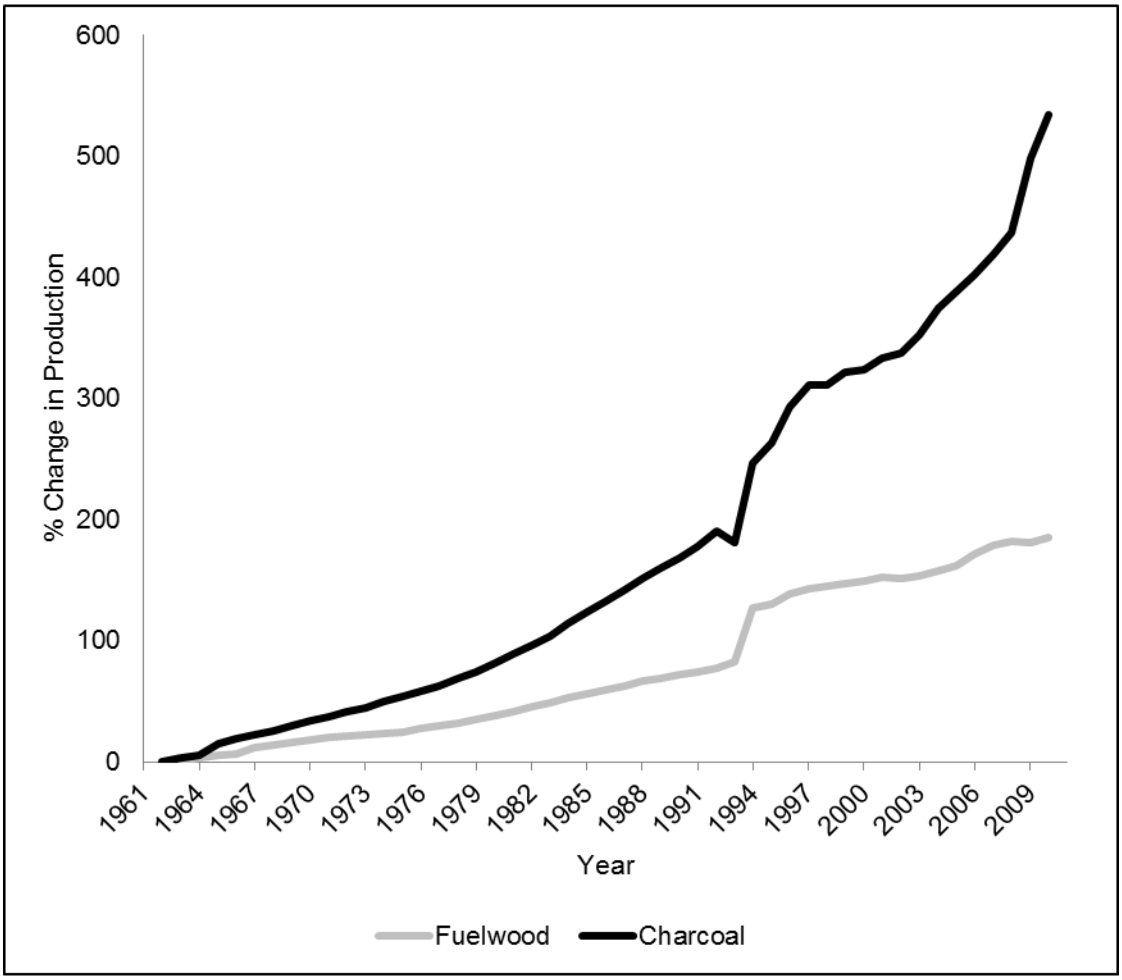
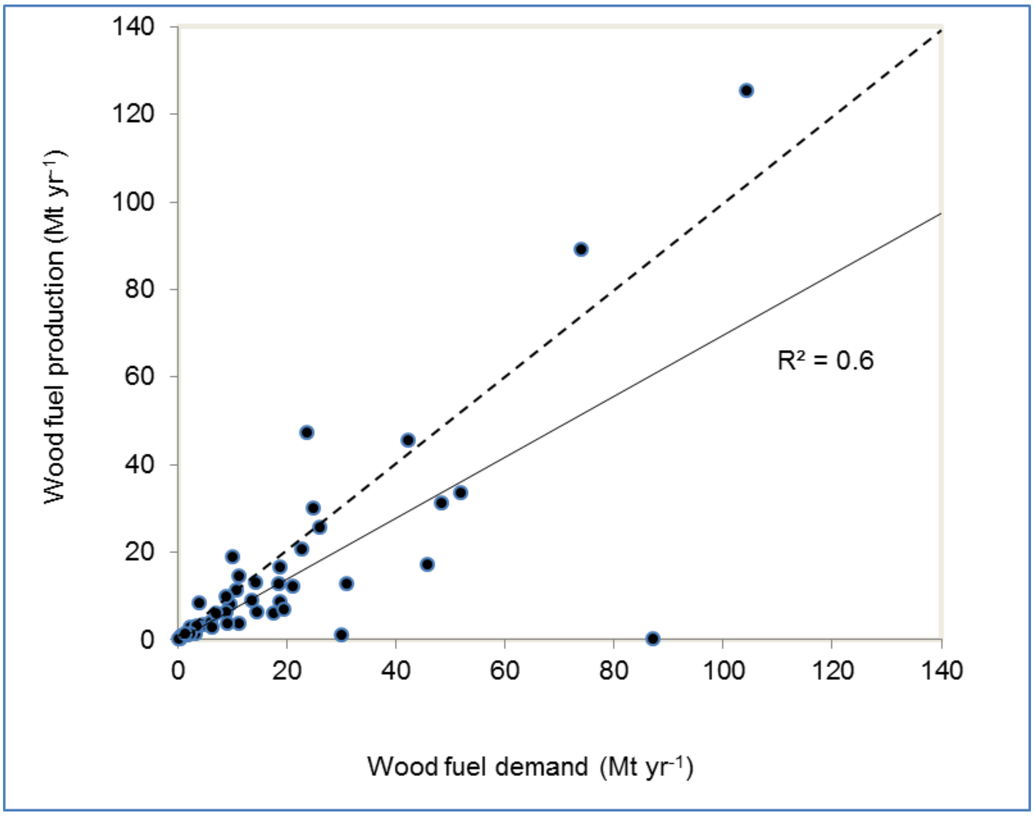

Fuelwood production (Mt y^{-1})
Charcoal production (Mt y^{-1})
500
450
400
350
300
250
200
150
100
50
0
35
30
25
20
15
10
5
0
1961
1971
1981
1991
2001
Year
Fuelwood
Charcoal

Fig. 2



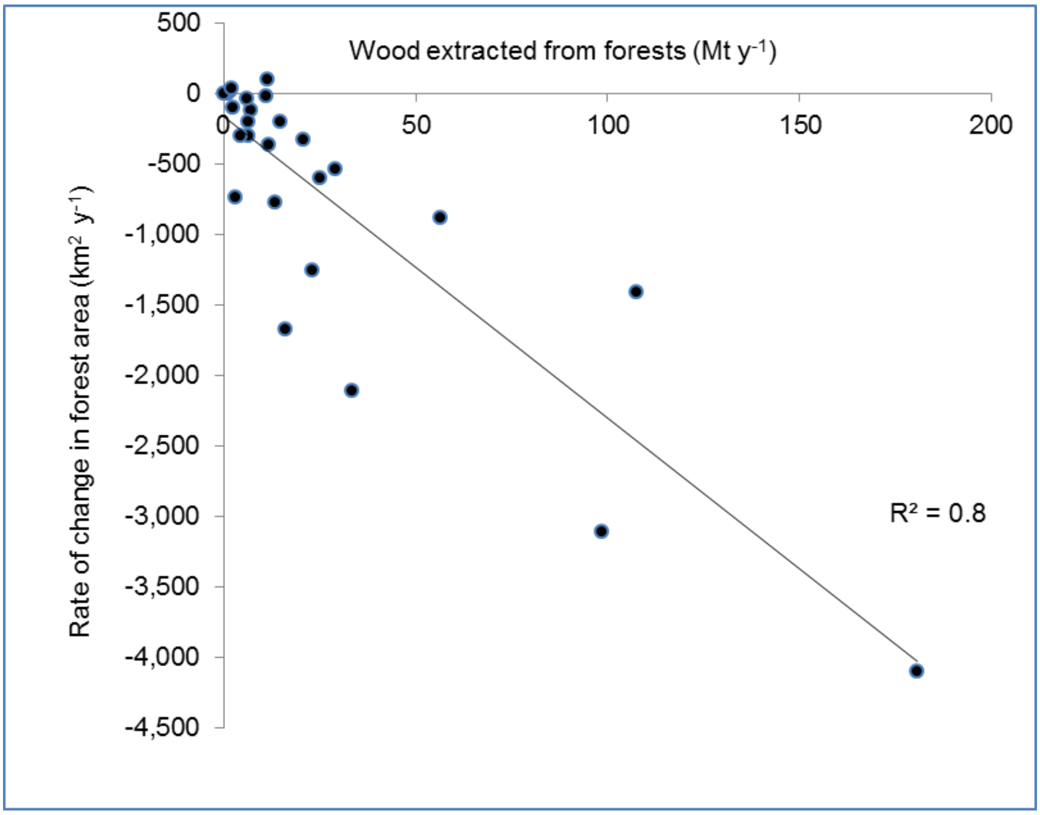
% Change in Production
600
500
400
300
200
100
0
1961
1964
1967
1970
1973
1976
1979
1982
1985
1988
1991
1994
1997
2000
2003
2006
2009
Year
Fuelwood
Charcoal

Fig. 3



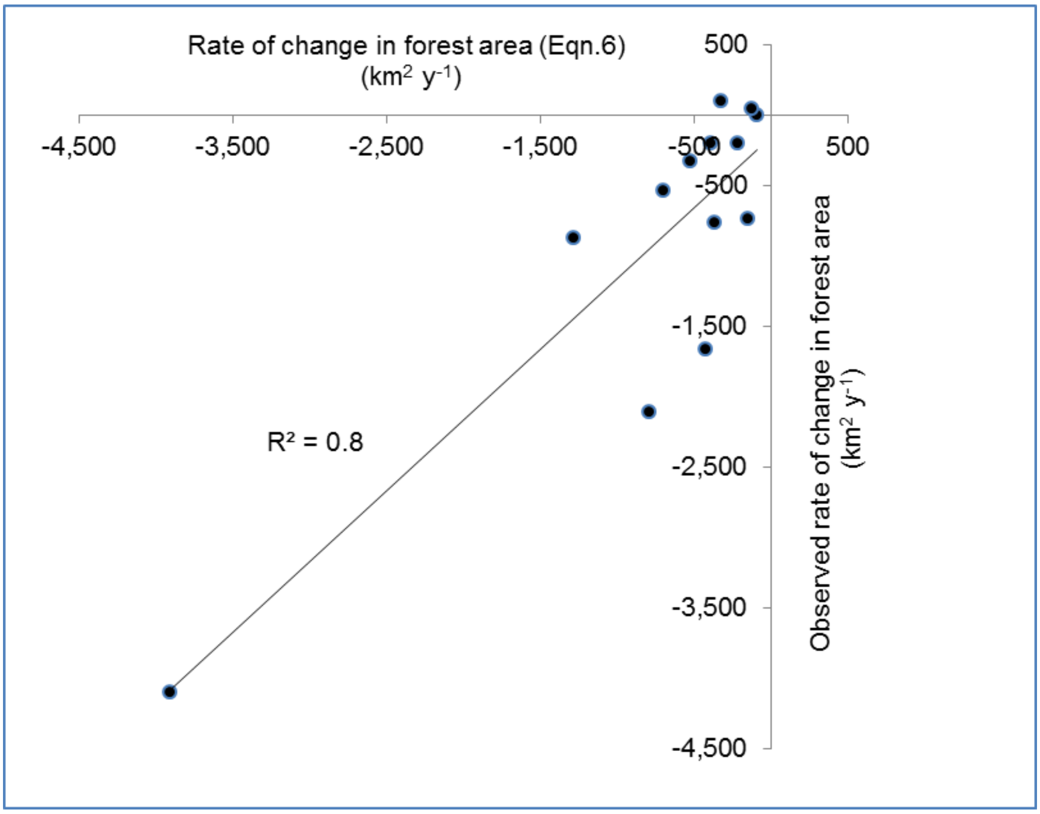
Wood fuel production (Mt yr-1)
Wood fuel demand (Mt yr-1)
R² = 0.6
0
20
40
60
80
100
120
140

Fig. 4



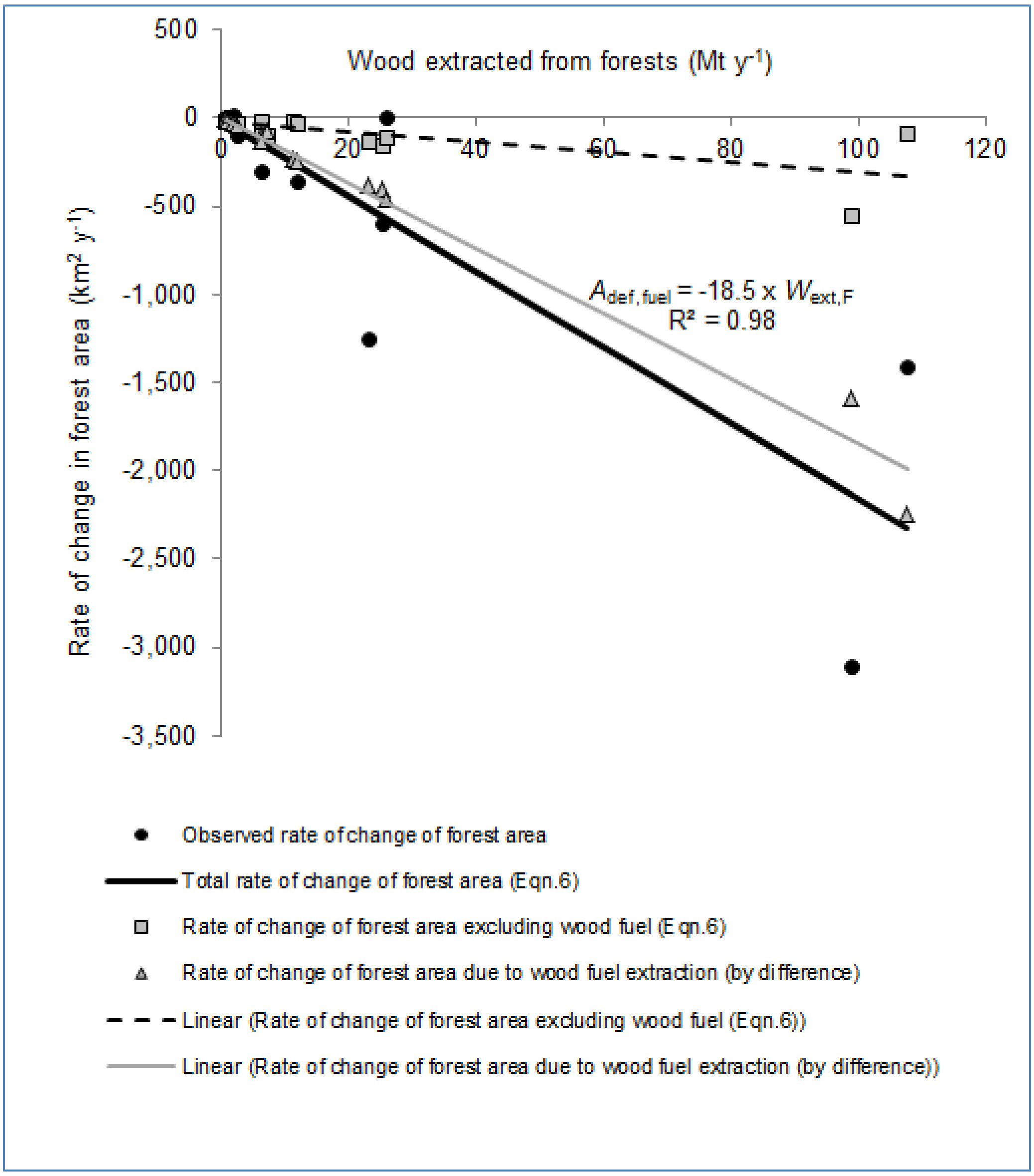
Wood extracted from forests (Mt y-1)
Rate of change in forest area (km2 y-1)
R² = 0.8
500
0
-500
-1,000
-1,500
-2,000
-2,500
-3,000
-3,500
-4,000
-4,500
0
50
100
150
200

Fig. 5.



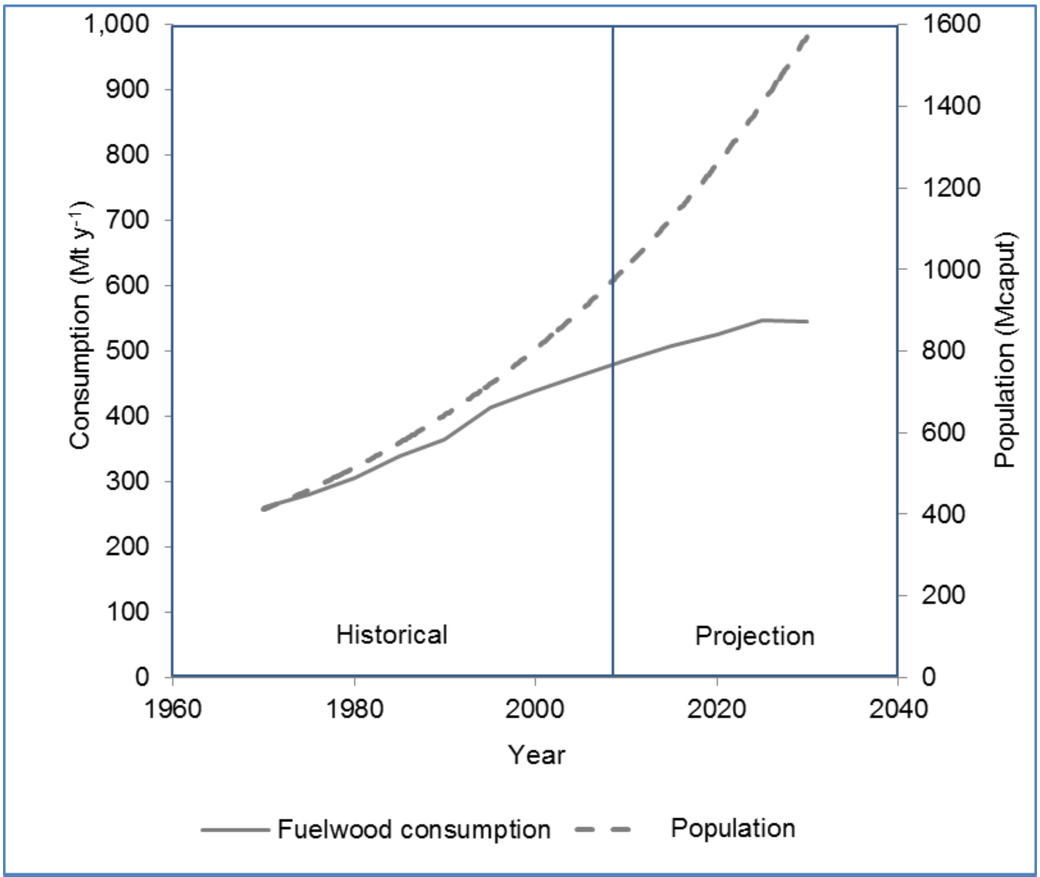
Rate of change in forest area (Eqn.6)
(km2 y-1)
500
-4,500
-3,500
-2,500
-1,500
-500
500
-500
-1,500
-2,500
-3,500
-4,500
R² = 0.8
Observed rate of change in forest area
(km2 y-1)

Fig. 6



Wood extracted from forests (Mt y-1)
Rate of change in forest area (km2 y-1)
500
0
-500
-1,000
-1,500
-2,000
-2,500
-3,000
-3,500
0
20
40
60
80
100
120
Adef,fuel = -18.5 x Wext,F
R² = 0.98
Observed rate of change of forest area
Total rate of change of forest area (Eqn.6)
Rate of change of forest area excluding wood fuel (Eqn.6)
Rate of change of forest area due to wood fuel extraction (by difference)
Linear (Rate of change of forest area excluding wood fuel (Eqn.6))
Linear (Rate of change of forest area due to wood fuel extraction (by difference))

Fig.7


Consumption (Mt y-1)
Population (Mcaput)
Historical
Projection
Year
Fuelwood consumption
Population

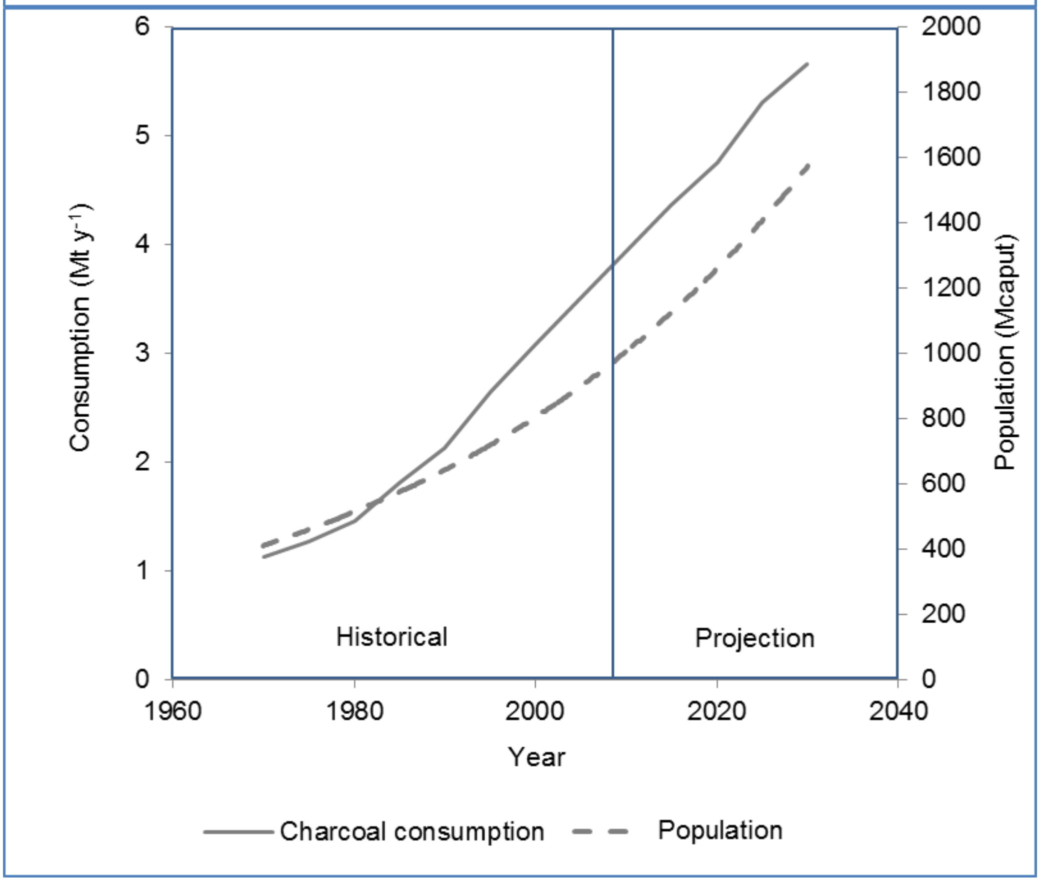
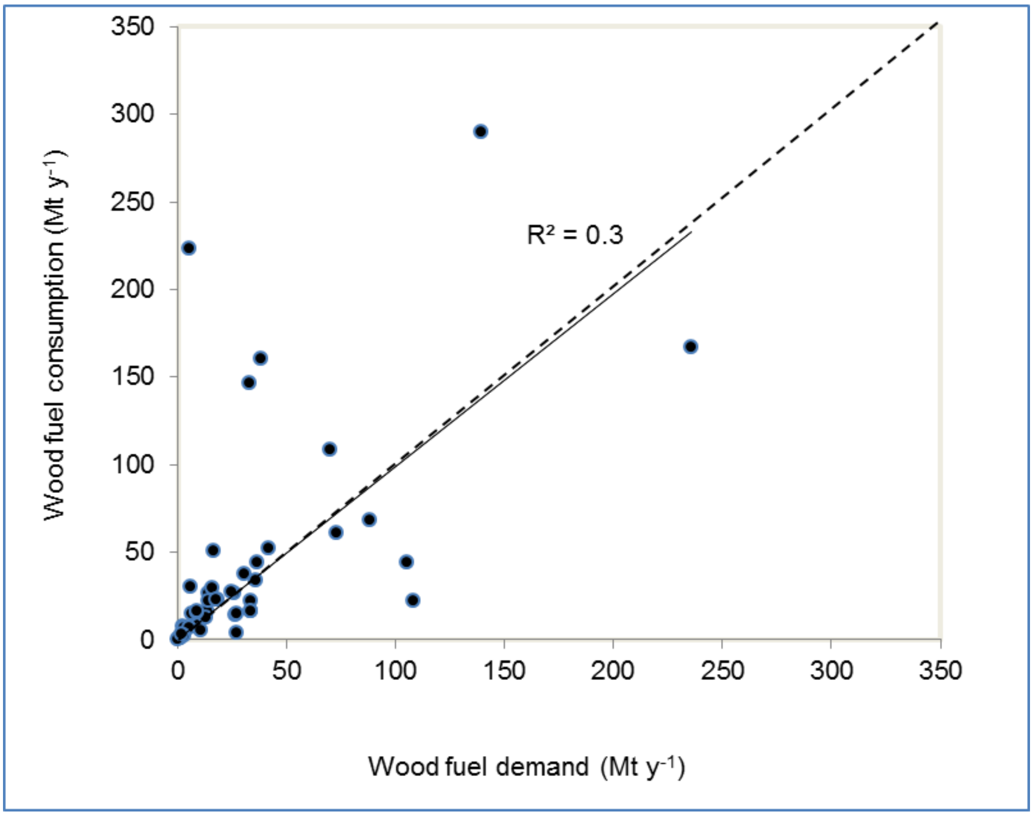
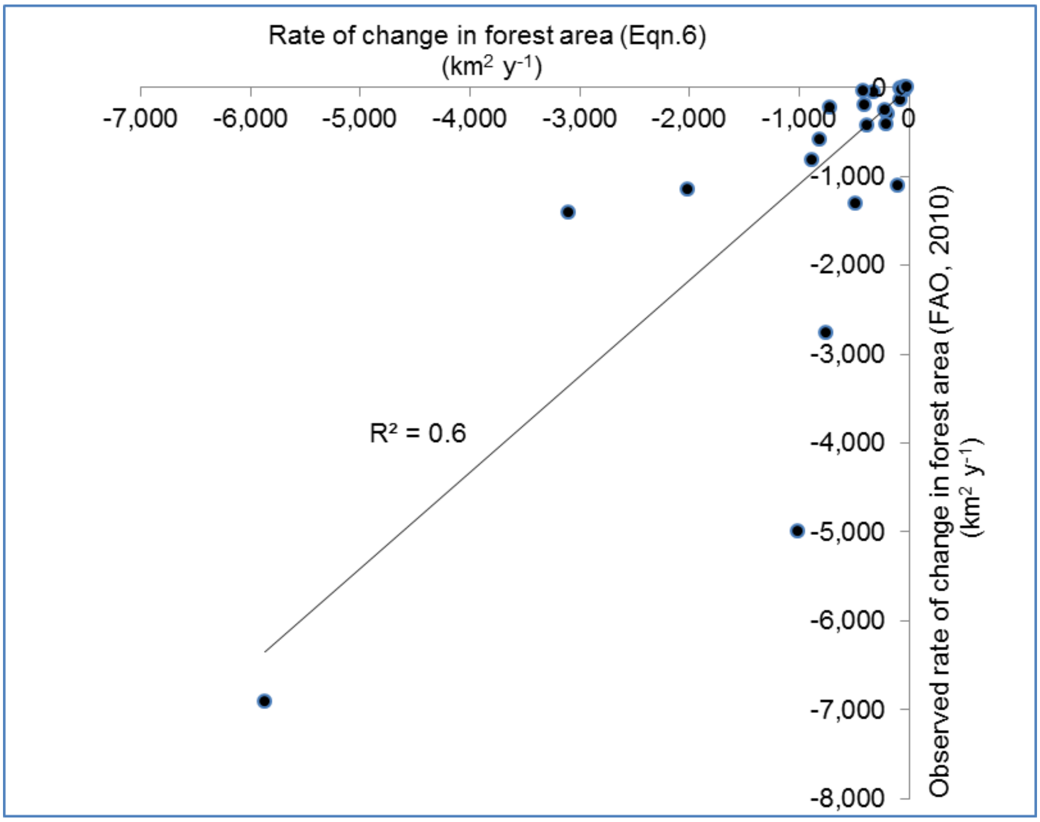

Consumption (Mt y-1)
Population (Mcaput)
Historical
Projection
Year
Charcoal consumption
Population

Fig. 8



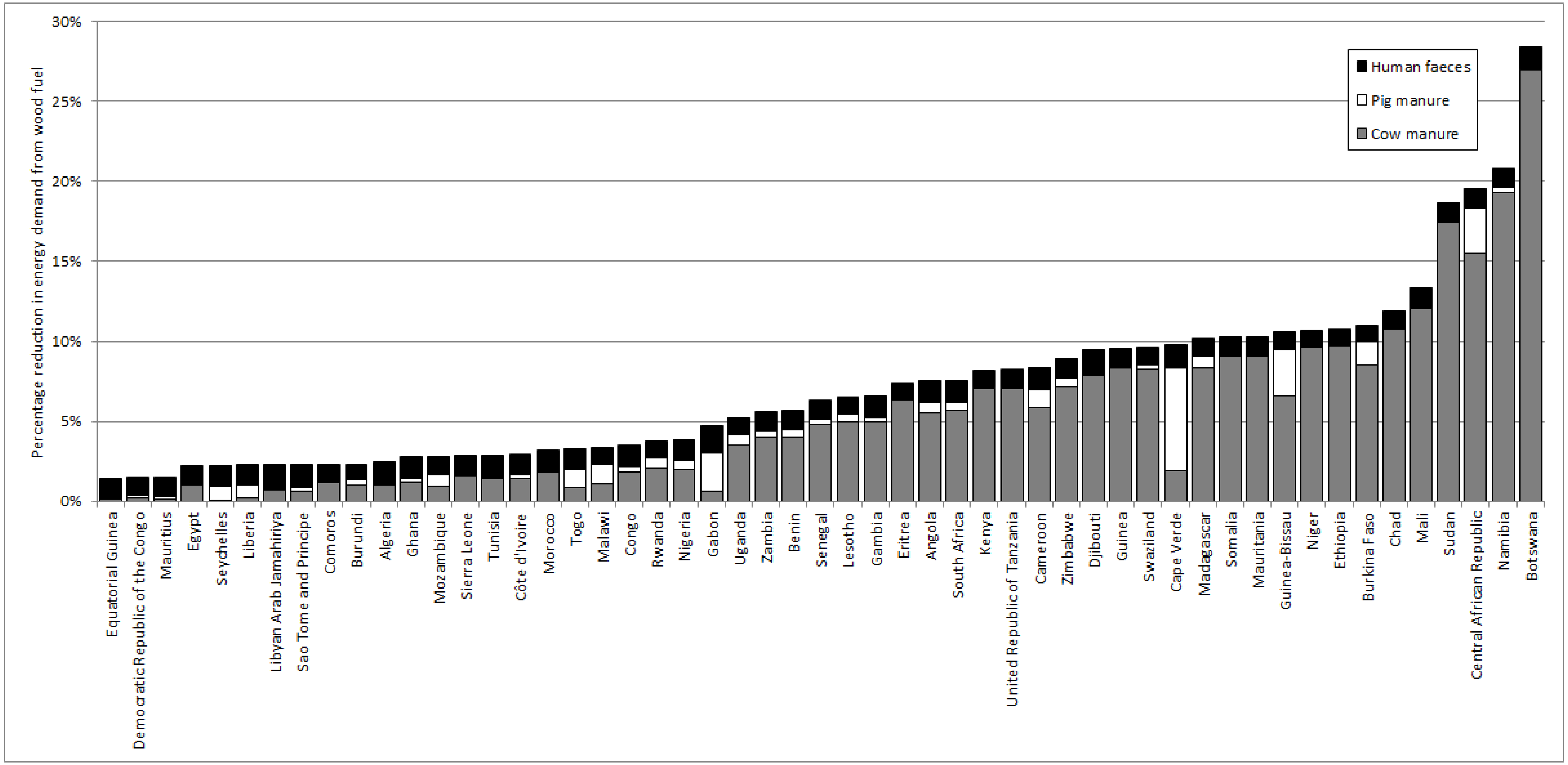
Wood fuel consumption (Mt y-1)
Wood fuel demand (Mt y-1)
R² = 0.3
0
50
100
150
200
250
300
350

Fig. 9



Rate of change in forest area (Eqn.6)
(km2 y-1)
-7,000
-6,000
-5,000
-4,000
-3,000
-2,000
-1,000
0
-1,000
-2,000
-3,000
-4,000
-5,000
-6,000
-7,000
-8,000
R² = 0.6
Observed rate of change in forest area (FAO, 2010)
(km2 y-1)

Fig. 10



Percentage reduction in energy demand from wood fuel
30%
25%
20%
15%
10%
5%
0%
Human faeces
Pig manure
Cow manure
Equatorial Guinea
Democratic Republic of the Congo
Mauritius
Egypt
Seychelles
Liberia
Libyan Arab Jamahiriya
Sao Tome and Principe
Comoros
Burundi
Algeria
Ghana
Mozambique
Sierra Leone
Tunisia
Côte d'Ivoire
Morocco
Togo
Malawi
Congo
Rwanda
Nigeria
Gabon
Uganda
Zambia
Benin
Senegal
Lesotho
Gambia
Eritrea
Angola
South Africa
Kenya
United Republic of Tanzania
Cameroon
Zimbabwe
Djibouti
Guinea
Swaziland
Cape Verde
Madagascar
Somalia
Mauritania
Guinea-Bissau
Niger
Ethiopia
Burkina Faso
Chad
Mali
Sudan
Central African Republic
Namibia
Botswana