Fuel from the Savannah: Understanding the Climate Change Impacts of Large-Scale Charcoal Production in Kenya

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ABSTRACT

Kenya consumes 4-7 thousand tons of charcoal per day. Much of Kenya's charcoal comes from shrubland or savannah. After harvest, this land may be allowed to regenerate, but increasingly charcoal is used as a means to clear land for crop cultivation. This is particularly true in Narok District, one of Kenya's main charcoal production areas and an increasingly important grain production zone. Land management specifically for charcoal is extremely rare. Charcoal production and use is associated with high greenhouse gas emissions relative to other common energy options. However, there have been few attempts to analyze the land-use change implications associated with different charcoal production systems, This paper uses computer modeling parameterized with empirical data to analyze the carbon dynamics of current charcoal production practices, including changes in stocks of soil and biomass carbon resulting from land cover change linked to charcoal production. On a life cycle basis, the common practice of charcoal production followed by grain cultivation leads to a loss of 40 tC per ha (2.7 tC per ton of charcoal produced). Charcoal production by coppice management of native vegetation releases 3-9 tC per ha over 50 years of management (0.08-0.3 tC per ton of charcoal produced). Charcoal production using a fast growing exotic species (*eucalyptus grandis*) managed on a 10-year coppice managed cycle results in a net sink of 150 tC per ha (0.5-0.8 tC sequestered per ton of charcoal produced). These results are compared to life cycle emissions from other common household fuels and policy implications are discussed.

ABBREVIATIONS USED IN THE TEXT

CAI	Current Annual Increment
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
EF	Emission factor
GHG	Greenhouse gas
GWI	Global Warming Impact
GWP	Global warming potential
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
KP	Kyoto Protocol
LCA	Life Cycle Assessment
LUC	Land-use change
NMHCs	Mon-methane hydrocarbons
PM	Particulate matter
tC	tons of carbon (also gC – grams of carbon)

INTRODUCTION

Kenya is one of the world's leading consumers of charcoal. Every day, between four and seven thousand tons are used in households, schools, and businesses across the country (Ministry of Energy 2002; Mutimba and Barasa 2005). To satisfy Kenya's daily charcoal demand, between 25 and 60 thousand cubic meters of woody biomass are carbonized each day. [1] Wood for Kenya's charcoal is harvested primarily from woody savannah and range lands that constitute over two thirds of the country's land mass (see Figure 1).

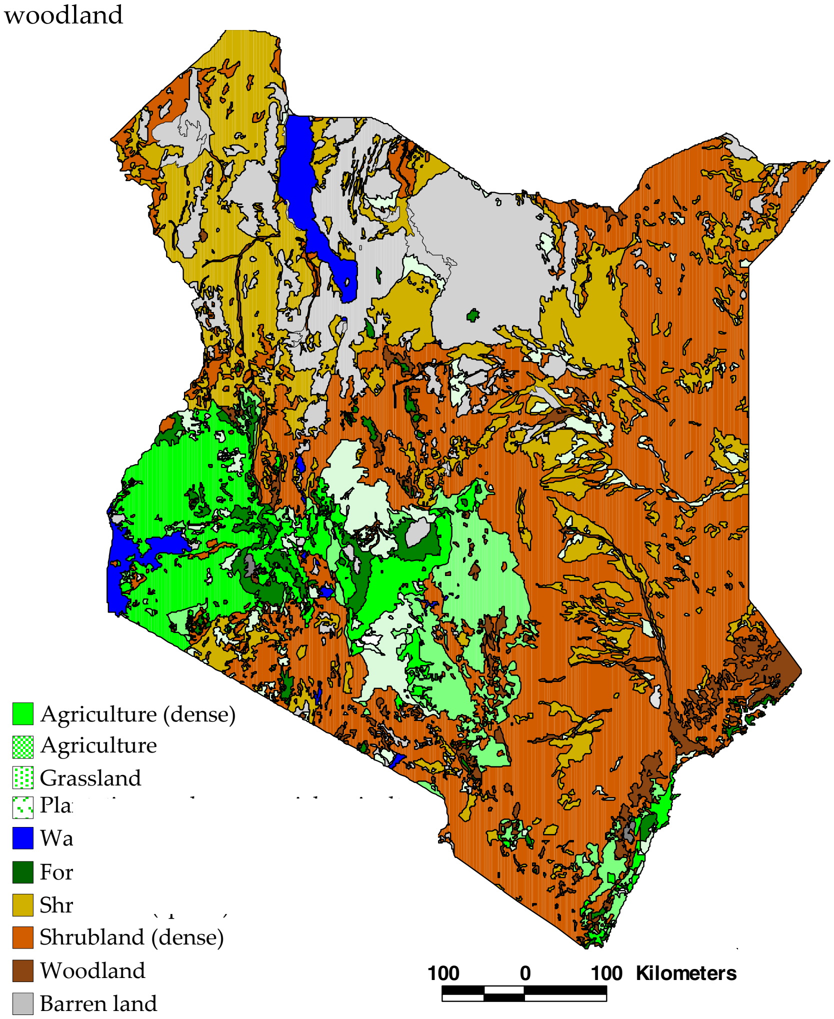
Charcoal production and consumption on this scale has far-reaching environmental and socio-economic implications. However, not all of the impacts associated with charcoal are negative. Although much of the literature holds that the charcoal trade is harmful to the environment because of the impacts that charcoal production can have on tree cover as well as the emissions that are associated with wood pyrolysis (Eckholm 1975; FAO 1978; Foley 1986; Smith, Pennise et al. 1999), there are also benefits associated with charcoal in the form of rural employment and reduced levels of indoor air pollution relative to fuel wood, which remains the primary source of residential energy for rural Kenyans.[2]

Relative to other common household fuels, charcoal is associated with particularly high greenhouse gas (GHG) emissions because of the nature the charcoal life-cycle and the physical properties of charcoal as a fuel (Pennise 2003; Bailis, Pennise et al. 2004). Through a life-cycle assessment (LCA) approach, this paper estimates the emissions from the charcoal life-cycle under several different charcoal production systems and compares these emissions to those associated with the life cycle of other common household fuels including fuelwood,[3] charcoal, kerosene, LPG, and electricity.[4]

As with any forest product, the life cycle of charcoal and other wood-based fuels incorporates both biological components and industrial or market-oriented components. Each component of the life cycle is linked to one another by the land-management decisions associated the woodfuel production system (Schlamadinger and Marland 1996; Schlamadinger, Apps et al. 1997). While charcoal is generally more GHG intensive than other household fuels, including petroleum-based fuels (Brocard, Lacaux et al. 1996; Smith, Uma et al. 2000; Bertschi, Yokelson et al. 2003; Pennise 2003; Bailis, Ezzati et al. 2005), I will demonstrate that the net emissions that result from its use depend strongly on the production system that is in place.

This work has important implications for Kenya and for many countries in sub-Saharan Africa, where the use of charcoal is widespread (Bailis, Ezzati et al. 2005). In Kenya, there is currently debate at the highest level of government over the role of the country's forest areas for both economic development and environmental conservation as well as more specific policy questions concerning wood, charcoal and other forms of energy (Okwemba 2003). The stakes in these debates have increased since late last year, when the Nobel Peace Prize was awarded to Prof. Wangari Wa Maathai, a famous Kenyan environmentalist. Dr. Maathai is one of the most vocal supporters of Kenya's forests and an outspoken critic of the country's heavy reliance on woodfuels (Bosire 2003).

Figure 1: Kenya land cover showing predominant shrubland and woodland



The issue extends beyond Kenya. Charcoal is a popular household fuel throughout sub-Saharan Africa. Across the region, roughly 25 million tons of charcoal will be consumed in 2005 (Bailis, Ezzati et al. 2005). Few countries have mechanisms in pla ce to ensure that production occurs on a sustainable basis. Kenya exemplifies this situation - charcoal exists at the margins of the law. Harassment of producers and traders is common including arrests, fines, and confiscations, as well as demands for bribes that can total as much as 30% of the charcoal's retail price.[5] Charcoal represents a massive transfer of resources from rural to urban and peri-urban areas, with very little reinvested in the areas where charcoal originates. By estimating the GHG balances associated with different charcoal production systems, I hope to draw attention to this very common, but neglected sector of the rural economy throughout sub-Saharan Africa and demonstrate that charcoal production represents an opportunity for investments in GHG mitigation that is linked very strongly to rural livelihoods.

This paper will focus primarily on the life cycle impacts of charcoal; however, in order to understand how these impacts compare to other household fuels, the life-cycle impacts of fuelwood and common fossil fuels will also be discussed. The remainder of this paper is divided into 4 remaining sections. In the following section, I will describe the charcoal production systems currently used in Kenya as well as several alternatives to these current systems, which have the potential to improve the livelihoods that people derive from charcoal production as well as reduce the Global Warming Impact (GWI) of charcoal-related activities. Following that, I will introduce the life cycle assessment models that I use to determine GWI from different charcoal production systems as well as briefly describe the models used to assess fossil fuel production systems. I will then present the results of these assessments in which I compare several charcoal production systems to other common household fuels. In the final section I will discuss the policy implications of these results and suggest some possible paths for future research.

CHARCOAL PRODUCTION SYSTEMS

The process of transforming wood into charcoal adds value to roughly cut wood, a very basic raw material. Charcoal is made by heating wood in an oxygen-deficient environment. The process, called pyrolysis, drives off the moisture and most of the volatile compounds in the wood, leaving behind mostly fixed carbon (Foley 1986). The end-product is lighter and volumetrically smaller than the original wood with a higher calorific value, which makes it more economical to transport. In addition to its favorable transport characteristics, charcoal is favored by consumers for several reasons. When used for cooking, charcoal requires less attention than a wood fire and produces less smoke.[6] In addition, it can be purchased in small quantities, stored indefinitely, and is cheaper to cook with than other fuels (Bailis 2004).

Charcoal can be made from nearly any form of biomass, including many types of agricultural residue and timber processing waste (Bailis 2004). However, nearly all charcoal consumed in Kenya and elsewhere in SSA is made from local tree species (Mugo 1999; Ministry of Energy 2002). Certain trees are preferred for charcoal, while others are known to produce an inferior product (Odour and Wekesa 2003). For example, in Kenya several species of Acacia are favored, although the use of over 200 different tree species has been recorded (Mutimba and Barasa 2005).[7]

There are several important factors that define systems of charcoal production. These include the type of land tenure arrangements, land management practices, and the production technology that is used. I will discuss each of these aspects briefly.

Land tenure and land management

In Kenya, the trees harvested for charcoal typically originate from one of three types of land tenure systems: private land, trust land and state-owned land.[8] Within each land tenure system, there are several types of land management practices with which charcoal is associated. On private land, charcoal is typically made from naturally occurring woody vegetation, when newly opened or fallow land is opened for cultivation. In addition, in some areas where farms are small but long-established, charcoal production also occurs when landowners harvest trees they have planted themselves. Usually these trees were planted for other purposes - for example, to provide fruit, building materials, or shade - but are used for charcoal when their original purpose has been met or in the event that the of a cash emergency (Chambers and Leach 1989; Mutimba and Barasa 2005). Table 1 describes some of the management practices associated with different types of private land as well as other tenure systems in which charcoal is made.

In this analysis, I will focus on charcoal production from private lands, which is the most common form of production in Kenya (Mugo and Ong 2003; Mutimba and Barasa 2005). This production system is often associated with land clearance for cultivation, pastoralism, or ranching. In the case of clearance for cultivation, charcoal is a by-product of land use change (LUC). In these cases, charcoal is useful in that its sale helps to offset the cost of clearing land. When this occurs, LUC is likely to be long-lasting or permanent.

In the case of charcoal production associated with ranching or pastoral land management, trees are usually selectively harvested. Trees of a specific species or size class are chosen while others are left behind (Mugo and Poulstrup 2003). These systems are subject to minimal silvicultural management and are left to regenerate naturally. Depending on the intensity and frequency of harvest as well as the occurrence of post-harvest practices such as burning or grazing, land cover may be restored over time. However, even in the absence of any land management, stand structure and species composition may be permanently altered.[9]

As Table 1 indicates, charcoal can be produced on private land under other management systems than clearance for cultivation or single tree harvest. For example, trees can be planted specifically for charcoal and harvested on a fixed rotation. This can occur on a range of scales from individual farmland to commercial plantations. Though technically feasible, this is extremely rare in Kenya.[10] The lack of tree planting is largely a result of charcoal's ambiguous legal status. In the current policy environment, there is no guarantee that trees planted for charcoal will be allowed to reach a market. However, as mentioned above, there are ongoing debates among policy makers that may lead to substantial changes in the way that charcoal is regulated. If such changes are implemented, it will enable individual farmers and commercial firms to invest in commercial charcoal production.[11, 12]

A second alternative to current practices is to integrate charcoal production into small-scale agricultural production. This could include many combinations of practices. For example, charcoal tree-crops can be grown concurrently with fruit tree crops or other cultivars in a multi-story agroforestry system. Alternatively, charcoal tree-crops could be used as part of an improved fallow system in which fallow fields are sown with nitrogen-fixing trees that can be harvested for fuelwood or charcoal after 3-4 years (Sanchez 1999).

Table 1: Land tenure system and management practices associated with charcoal production

Land tenure system	Management practices associated with charcoal production
Private land:	
Small farms (*shambas*)	Trees planted for various purposes may be used for charcoal after those purposes are met or in response to cash emergency (*common in some areas*). Opening new land or clearing fallow land for cultivation (*common in some areas*). Trees planted specifically for charcoal (*very rare*).
Commercial farms	Opening new land or clearing fallow land for cultivation (*common in some areas*).
Tree plantations	Silvicultural management – trees planted commercially for charcoal (*rare*) or planted for another purpose (timber, fruit, tannin extraction) with non-merchantable portion used for charcoal.
Private or Group ranches	Ranching and pastoral land management – landowners (individual or communal) can permit charcoal burners to cut trees and make charcoal, possibly for a fee (*legal*). Occasionally, charcoal makers may also "poach" trees from ranches (*illegal*).
Trust land:	Trees may be poached (*illegal*) or charcoal makers may seek permission from local governing body.
State-owned land:	
State Forests and National Parks	Trees are poached specifically for charcoal or for timber with non-merchantable portion made into charcoal (*illegal*). "Squatting" – forest area is cleared for cultivation and/or settlement; charcoal is made from slash (*illegal*).

CHARCOAL PRODUCTION TECHNOLOGY

Charcoal production systems are also characterized by the production technology that is used. Charcoal can be produced by a range of methods, from simple earth kilns to brick or metal kilns. In more industrialized settings, retorts can be used to capture condensable compounds, which can be redirected into the kiln and burned to generate needed for the charcoal-making process. In addition, some of the condensable compounds have value in other markets and can be extracted and so ld (FAO 1983; FAO 1985; Foley 1986). The earth kiln is the most common method of making charcoal in Kenya, as well as in the rest of sub-Saharan Africa. These may be associated with low yields and large emissions of pollutants like carbon monoxide (CO) and unburned hydrocarbons.[13] These emissions result in substantial climate impacts from charcoal relative to other forms of household fuel. This is described in more detail below.

Improved charcoal production technologies have been introduced in order to increase production efficiency and reduce the emissions of potentially harmful pollutants. However, the use of these technologies remains very low because of limited awareness, weak technical capacity, and high risks to investment. If investment in carbon emissions mitigation were directed to the charcoal sector it would facilitate the introduction of this technology, as I will demonstrate below.

Various production technologies can be combined with any one of the land management systems described above. Each integrated system has different implications for the fate of carbon in the ecosystem. In this paper, I compare the GHG emissions associated with Kenya's current predominant charcoal production systems, which are characterized by land clearance for crop cultivation or itinerant charcoal production on rangeland using earthen kilns to two groups of alternative models, which include land management practices specifically for charcoal production as well as the integration of improved kilns into production systems.

In Kenya's Narok district, one of Kenya's most important charcoal production areas and the focal area of my research, charcoal is produced on land that is being cleared for cultivation. However, it is not uncommon for the land to remain uncultivated for many years after clearing. I use the production practices in this region as the basis for the models that I explore below. In this area, large communal ranches were recently subdivided, a process that gave each male household head title to a plot of land.[14] In comparison to neighboring districts, landholdings in Narok are large. Typical farm sizes range from 30-200 acres (13-84 ha), whereas farm sizes in neighboring districts are typically between 2 and 3 acres per household (0.8-1.3 ha). Many plots are being completely cleared, with charcoal production helping to finance the costs of clearing. Figure 2 shows land cover in the district and a typical area of shrubland. The density of woody biomass is such that substantial labor must be mobilized to clear land for cultivation. Many landowners do not have access to sufficient capital to clear and/or cultivate more than a few acres. Thus, I wish to examine the feasibility of managing some portion of a newly subdivided plot for charcoal production using native vegetation (*Tarchonanthus camphoratus*). This requires minimal inputs and could yield more benefits to the land owner than simply relying on charcoal as a one-time activity to open land. In addition, I will compare this option to a second model that allows for clearance of natural vegetation, followed by the planting of fast growing exotic tree species (*Eucalyptus grandis*) for charcoal production. These options are explained in Table 2 and form the basis for the models I explore below.

LCA MODELS FOR CHARCOAL AND OTHER HOUSEHOLD FUELS

General background

Life cycle assessment (LCA) is a means to evaluate the environmental burdens associated with particular goods (and services) by identifying and, if possible, quantifying energy and material usage and releases of pollution or other forms of waste associated with the production, consumption and disposal of the good (or the provision of the service). LCA also estimates the environmental impact of the energy and material flows. Finally, if possible, LCA attempts to evaluate options that may result in reductions of those impact s (Graedel 1998).

A general approach to LCA for a given activity can be summarized in a matrix that places processes on one axis and impacts on another as in Table 3.

Table 2: Baseline and alternative models of charcoal production

Land tenure system	Management practices associated with charcoal production
Private land:	
Small farms (*shambas*)	Trees planted for various purposes may be used for charcoal after those purposes are met or in response to cash emergency (*common in some areas*). Opening new land or clearing fallow land for cultivation (*common in some areas*). Trees planted specifically for charcoal (*very rare*).
Commercial farms	Opening new land or clearing fallow land for cultivation (*common in some areas*).
Tree plantations	Silvicultural management – trees planted commercially for charcoal (*rare*) or planted for another purpose (timber, fruit, tannin extraction) with non-merchantable portion used for charcoal.
Private or Group ranches	Ranching and pastoral land management – landowners (individual or communal) can permit charcoal burners to cut trees and make charcoal, possibly for a fee (*legal*). Occasionally, charcoal makers may also "poach" trees from ranches (*illegal*).
Trust land:	Trees may be poached (*illegal*) or charcoal makers may seek permission from local governing body.
State-owned land:	
State Forests and National Parks	Trees are poached specifically for charcoal or for timber with non-merchantable portion made into charcoal (*illegal*). "Squatting" – forest area is cleared for cultivation and/or settlement; charcoal is made from slash (*illegal*).

Figure 2: Land cover in Narok District and typical area of dense shrubland

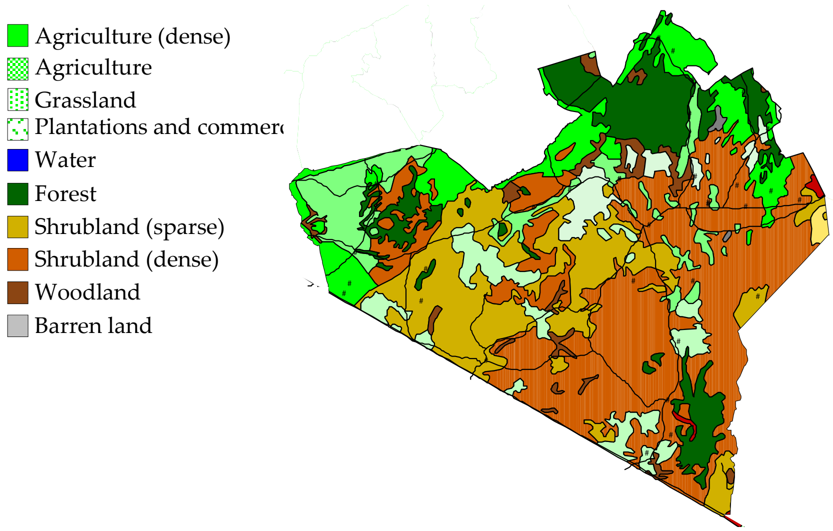


Table 3: Life cycle stages and possible environmental concerns associated with each stage (adapted from (Graedel 1998))

	Broad environmental concerns	*Specific processes or material flows*
Raw materials extraction		
Production		
Distribution		
Utilization		
Disposal		

As Table 3 indicates, impacts can be described as either broad environmental concerns or specific processes or material flows that affect those concerns. Broad environmental concerns include, inter alia, climate change, biodiversity loss, ozone depletion, water quality, resource depletion, and air quality.[15] Specific processes include the generation of solid wastes, water contaminants, and airborne pollutants, as well as energy requirements. These categories can be broken down further to their constituent parts as will be done for airborne pollutants in this analysis.

In developing the LCA, each cell of the matrix can be assessed quantitatively with continuous or discrete variables. They can also be assessed qualitatively as better, worse, or the same as some reference or baseline process (Graedel 1998). LCA for climate change from household energy use

This LCA, which is specifically designed to assess the impacts of household energy consumption on climate change, is focused primarily on the emission of greenhouse gases (GHGs) associated with the production, distribution and final consumption of common household fuels. In addition, land use change (LUC), leading to an additional flux of GHGs, is an important component of the analysis. This is particularly important because the principal activity under consideration is biomass-based energy production (IPCC 2000; Matthews 2001; Lettens, Muys et al. 2003); however, LUC can also play a role in the climate impact of other forms of energy provision (Pacca and Horvath 2002). As mentioned above, LCA typically analyzes five life cycle stages: Raw material extraction; Production; Distribution; Consumption; and Disposal. Each of these stages can have climate-related impacts associated with it, although some stages have larger impacts than others. Table 4 describes the processes and impacts that are associated with each stage for different household energy systems.

As Table 4 illustrates, most fuels are associated with some climate impacts at each stage of the life cycle with the exception of disposal. In the remainder of this section, I will describe the methods utilized to estimate climate impacts of each life cycle stage for each household fuel.

There is no single model that estimates the flows of matter and energy associated with the production and use of household fuels in developing countries. In order to make these estimations I use a several different models, some of which are available to the general public and some of which I have developed based on empirical measurements of emissions from household fuel combustion. Each model targets one or more of the life cycle stages for each fuel and develops an emissions factor (EF). This factor defines a ratio of GHG emissions to the quantity of fuel produced or consumed in each life-cycle stage. The results are then aggregated to give a net emissions factor for each fuel.[16]

The life cycles of both wood and charcoal incorporate biological as well as non-biological components, but neither is heavily industrialized. Fuelwood is typically harvested by manual labor and transported only short distances. People collect fallen wood and dead branches rather than cut live trees and, with the exception of cutting the wood to a useful size and tying it with vines or rope, the wood is not processed or packaged in any way (Leach and Mearns 1988). Wood for charcoal is usually harvested manually also, though occasionally gasoline powered tools are used. It is carbonized and packaged for transport on-site and may be transported long distances to retail points before it is sold to the final consumer (Kituyi 2004). In contrast to woodfuels, the life cycles of fossil fuels are fully industrialized with complex life cycles. Schematic models representing the life cycle of each fuel are shown in Figure 3a-c. The methods used to assess climate impact of each life cycle stage are discussed in detail below.

Table 4: Processes and impacts associated with life cycle stages of household energy options in Kenya [a]

Life cycle stage	Household Fuel Source			
	Fuelwood	Charcoal	Kerosene and LPG	Electricity [b]
Raw materials extraction	Wood growth and harvest: C-seq, possible LUC	Wood growth and harvest: C-seq, possible LUC	LUC, GHGs	Hydro LUC, GHGs Thermal LUC, GHGs Geothermal LUC, GHGs
Production	No post-harvest production processes	Wood carbonization: greenhouse gases, LUC	Refining: GHGs	Hydro no impact Thermal GHGs Geothermal no impact
Distribution	Transport by animate power: no impact	Transport by mechanized vehicles: GHGs	Transport by pipeline, ships, and vehicles: GHGs	Transmission: No impact
Utilization	GHGs	GHGs	GHGs	No impact
Disposal	No impact	No impact	No impact	No impact

[a] Note this analysis only accounts for the life cycle stages of the each fuel (or electricity). It does not account for the possible impacts associated with the life-cycle of the stoves that are utilized with each fuel.

[b] Kenya's installed power generation capacity includes a mix of domestic and imported hydroelectric (61%), petroleum-based thermal (34%), and geothermal (5%) power generation (AFREPREN 2004).

Figure 3a: Model of fuelwood LCA

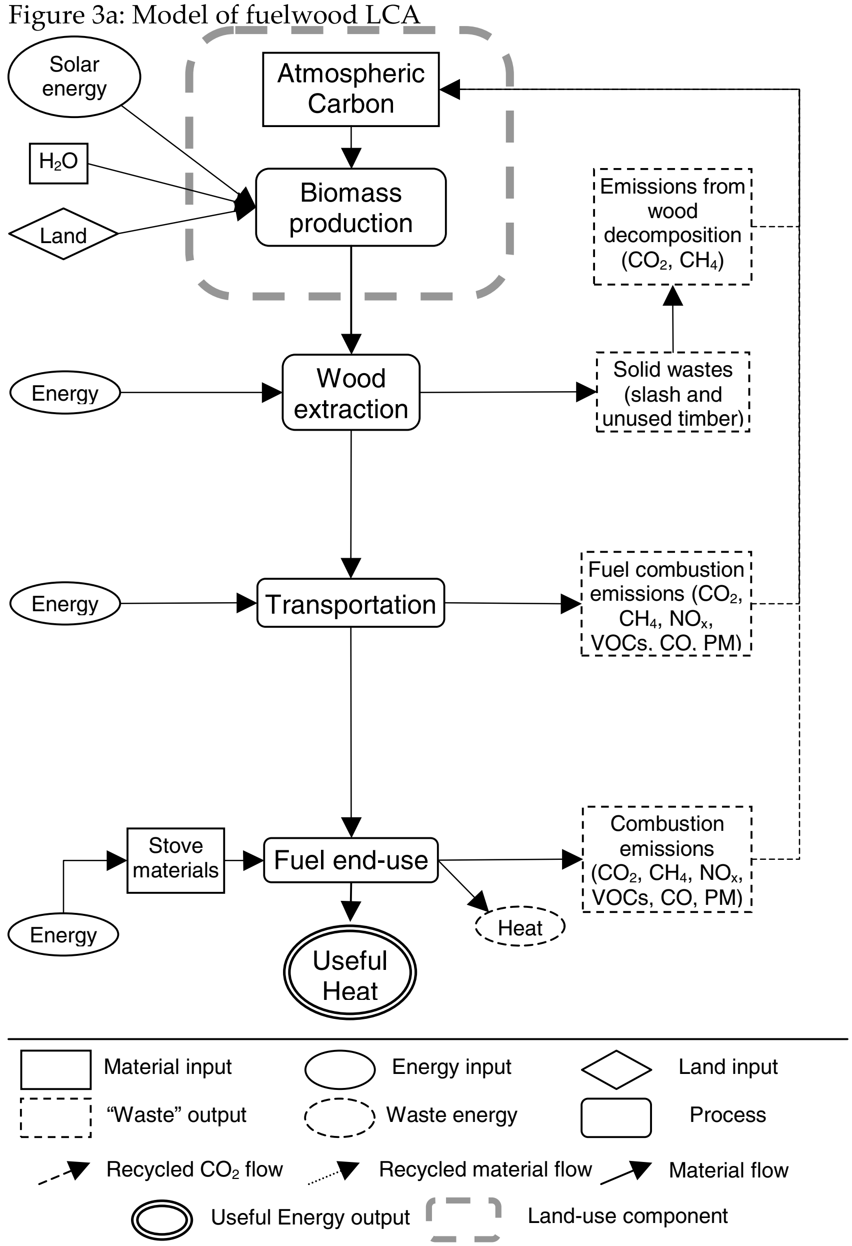


Figure 3b: Model of Charcoal LCA

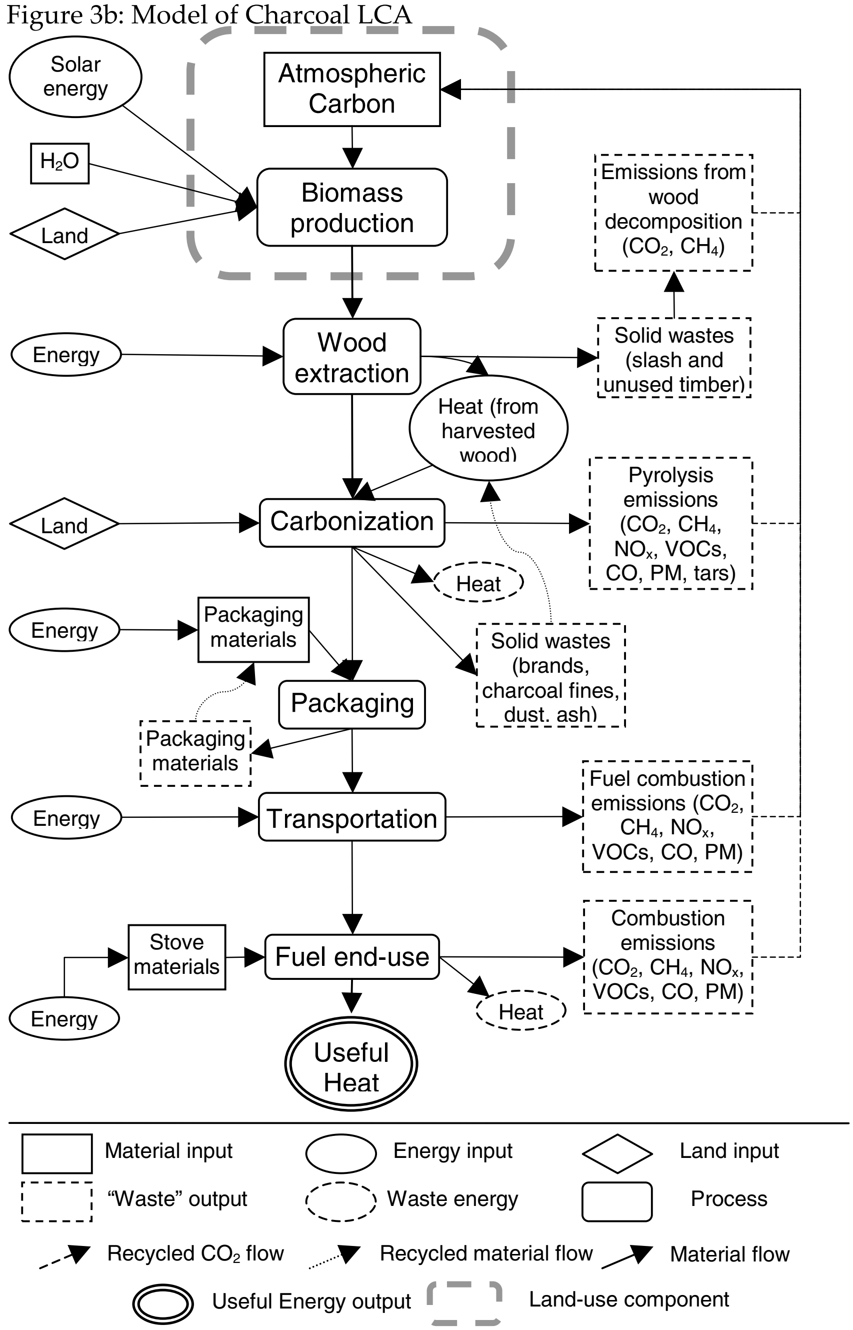
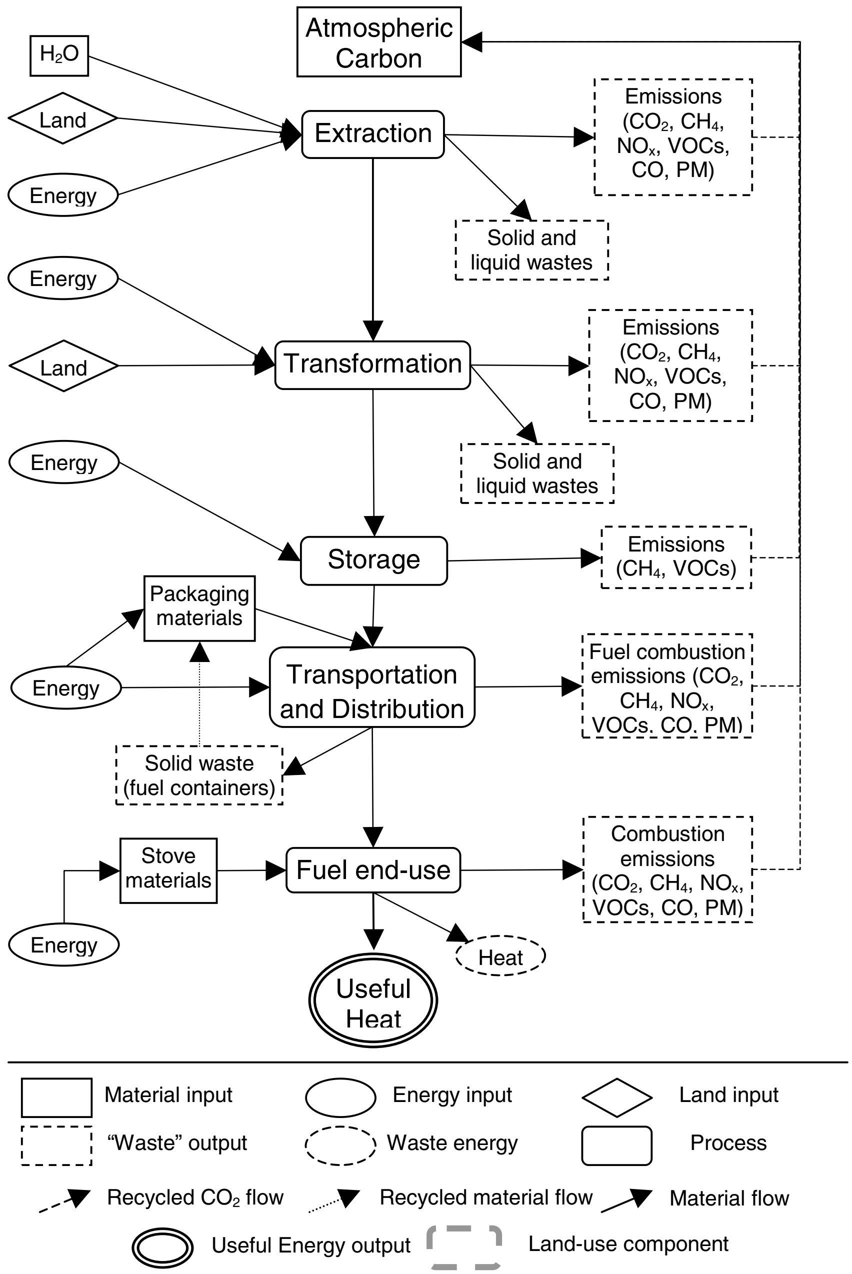


Figure 3c: Model of Fossil Fuel LCA



LCA FOR EACH HOUSEHOLD FUEL

Fuelwood and Charcoal

In this section, the GHG emissions from each stage of the fuelwood and charcoal life cycle are quantified. The emissions from production and end-use of woodfuels have been described elsewhere (Smith, Pennise et al. 1999; Smith, Uma et al. 2000; Pennise, Smith et al. 2001; Bhattacharya, Albina et al. 2002; Bailis, Ezzati et al. 2003; Pennise 2003; Bailis, Ezzati et al. 2005; Bailis, Ezzati et al. 2005), however researchers have yet to fully integrate the impacts of LUC associated with woodfuel production into analyses of these systems. Thus, emphasis is placed on the emissions resulting from LUC at the raw material extraction stage. Other stages of the woodfuel life cycle are also described briefly.

Fuelwood is also included in this section; however, as explained in Table 4, it is not closely associated with LUC and undergoes no real processing. Moreover, it is typically consumed close to the point of harvest. In contrast, charcoal undergoes substantial processing and it may be transported several hundred kilometers from the point of harvest and production to the point of consumption. Thus, most of the analysis in this section is focused on charcoal, though fuelwood will be discussed where relevant. For example, there are end-use emissions associated with the consumption of both fuelwood and charcoal.

Raw material extraction and fuel production

The impacts of fuelwood and charcoal production depend on the method and intensity of wood harvesting as well as the post-harvest land management practices. For fuelwood, this analysis models current behavior of fuelwood users in Kenya. Wood is harvested manually from fallen branches, dead wood, or parts of trees that have been cut for other purposes, so that are no emissions associated with the harvest. Nor are there emissions resulting from long-term land use change. Charcoal production also begins with manual wood extraction. However, as discussed above, charcoal production can lead to long-term changes in land cover because of it involves the harvest of entire trees or stands of trees and because it is often associated with changes in land-use.

Thus, for all charcoal production systems, this life-cycle stage is associated with changes in terrestrial carbon resulting from long-term LUC. These changes can be quantified by modeling stocks and fluxes of carbon at the stand level, which is the approach used in this analysis.

The model that was used is CO2FIX (Version 3.1) (Nabuurs, Garza-Caligaris et al. 2001; Masera, Garza-Caligaris et al. 2003).[17] In this model, the total stock of carbon stored in a stand of trees at any time is modeled as the sum of three carbon stocks:

$$C_{Tt} = C_{bt} + C_{st} + C_{pt} \text{ (tC ha}^{-1}\text{)} \quad [1]$$

Where t is the time period under consideration, C_{Tt} is the total stock of carbon, C_{bt} is the total carbon stored in living biomass, which includes both above-ground (AG) and below-ground (BG) biomass, C_{st} is the carbon stored in soil organic matter (SOM), and C_{pt} is the carbon stored in wood products (in this case wood that is harvested and subsequently converted to charcoal). All stocks are measured in tons of carbon per hectare (tC ha^{-1}). The model treats each component in eqn. 1 as a separate module. A schematic diagram of stocks and flows accounted for by each module of the model is shown in Figure 4 (each module is distinguished by broken gray lines).

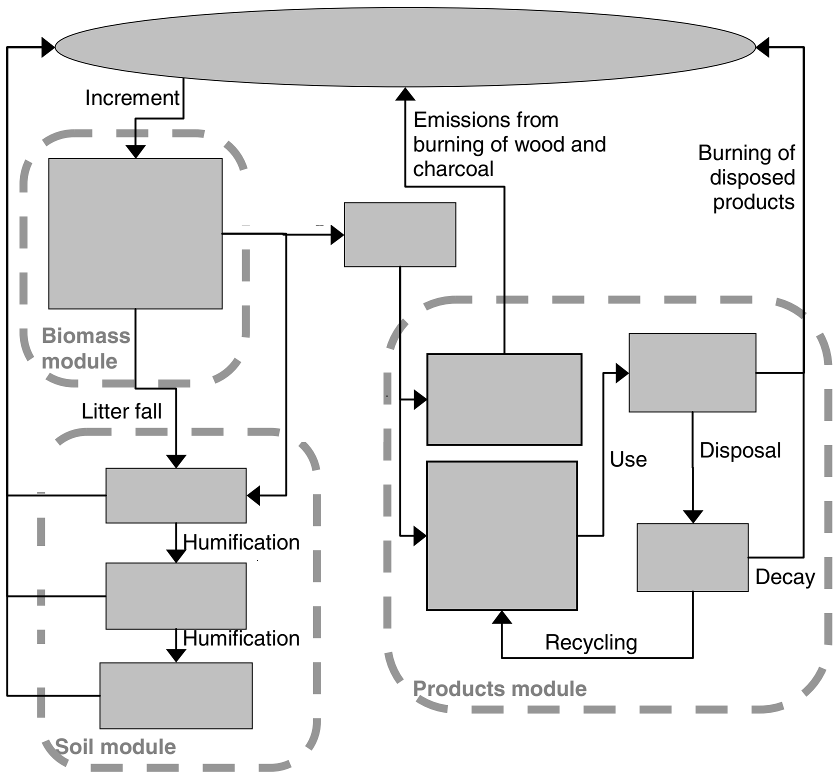
From one time period to the next, carbon flows within and between modules as depicted by the arrows in Figure 4. After a time period of n years, the net flux of carbon can be determined by taking the difference:

$$\Delta C_T = C_{Tn} - C_{T0} \quad \text{or}$$
$$\Delta C_T = \Delta C_b + \Delta C_s + \Delta C_p = (C_{bn} - C_{b0}) + (C_{sn} - C_{s0}) + (C_{pn} - C_{p0}) \quad [2]$$

In some circumstances, for example, in coppice systems, C_{Tn} is cyclic and it is more appropriate to calculate a time average carbon stocking level, where, for period of n years:

$$\overline{C}_T = \frac{1}{t_n - t_0} \sum_{i=0}^{n} C_{Ti} \quad [3]$$

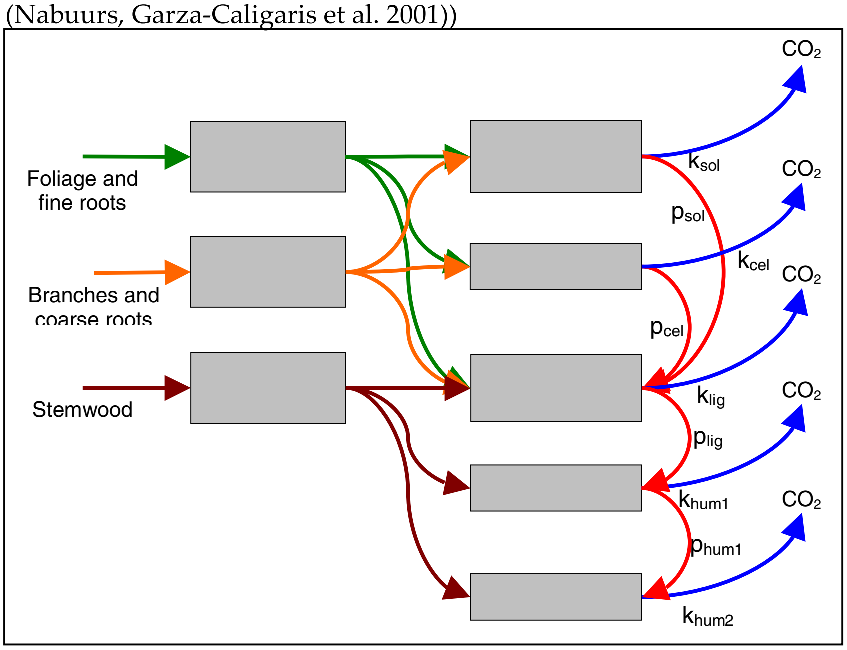
Figure 4: Land-use change model for estimating emissions from wood harvesting - adapted from (Nabuurs, Garza-Caligaris et al. 2001)



In order to accurately simulate carbon dynamics for a given stand of trees, each module must be parameterized according to the physical properties of that stand. The biomass module is parameterized by inputting biomass growth and turnover, wood density and carbon content, factors accounting for competition among and between cohorts of trees, natural mortality (senescence), and harvest-induced losses. In addition, thinning and harvesting schedules are input.

The soil module incorporates a dynamic soil carbon model that has been shown to robustly estimate decomposition rates for different types of litter across a range of climatic conditions (Liski, Nissinen et al. 2003). The model assumes carbon is input to the soil via litter as depicted in Figure 4. The litter is divided into three compartments: coarse woody litter consisting of stemwood, fine woody litter consisting of branches and coarse roots, and non-woody litter consisting of foliage and fine roots. The rate of carbon input into each litter compartment is determined by the growth and turnover rates, as well as inputs arising from mortality and harvest wastes (slash) defined in the biomass module. Depending on its chemical composition, the litter is partitioned into one of three subsequent compartments: soluble compounds, holocellulose, and lignin-like compounds. The rate of this partitioning depends on temperature and water availability. In addition to these compartments, which constitute the labile pool of soil carbon, there are two humus compartments. Each compartment (denoted here by the subscript i) has a specific decomposition rate (k_i). The soluble compounds and holocellulose compartments send a fraction of their carbon ($p_{sol,cel}$) to the lignin-like compartment; the remainder ($1-p_{sol,cel}$) leaves the system. Similarly, lignin-like compounds are transformed at a rate defined by k_{lig}. A fraction (p_{lig}) undergoes humification and enters the first humus compartment, while the remainder ($1-p_{lig}$) leaves the system. Carbon leaves the first humus compartment each period in a similar way, with a fraction (p_{hum1}) transferred to the second (recalcitrant) humus compartment, and the remainder ($1 - p_{hum1}$) leaving the system. Lastly, the remaining carbon slowly leaves the soil system entirely, returning to the atmosphere at a rate defined by k_{hum2}. The entire process is depicted in Figure 5.

Figure 5: Stocks and flows of carbon in the soil module (adapted from (Nabuurs, Garza-Caligaris et al. 2001))



Finally, there is the product module. This part of the model tracks the carbon in the harvested wood. If the forest stand is being exploited for long-lived products, the product module can be an important sink for harvested carbon. However, in the case of stands that are managed strictly for energy, there are no long-lived products and all of the carbon in wood harvested in a given period is released to the atmosphere in that period. These emissions are discussed further in the consumption stage below.

The parameters for the biomass and soil modules are taken from a series of studies that have been done in woodlands with similar characteristics. This model was not designed to calculate carbon stocks and flows for stands under a coppice management system. The model assumes that all biomass, including belowground components, enter either the pool of products or the pool of litter upon harvest. However, in a coppice system, the belowground biomass remains in the pool of living biomass for the next coppice cycle. Moreover, because of a well-established root mass, the rate of stem growth in subsequent generations of coppice is typically faster than stem growth in trees planted from seed or seedlings.

This problem was overcome by linking together a series of cohorts within a single model to represent each generation of coppice. Thus, at the end of the nth coppice cycle, all of the aboveground biomass components are removed and used for charcoal production. However, the belowground biomass and soil carbon that has accumulated during the nth cycle is used to define the initial root mass and soil carbon for the $(n+1)^{th}$ cycle. The plot in Figure6a and b show the estimated carbon stocks in above-ground (AG) and below-ground (BG) biomass as well as soil carbon in a stand of native shrubs. Figure 6a shows a hypothetical undisturbed stand. Figure 6b shows the same stand harvested at year 30 and subsequently managed on a 10 year coppice cycle.

In total, six land management schemes were analyzed. Each scheme started with an identical stand of woody shrubland (consisting primarily of *Tarchonanthus camphoratus*, the dominant tree cover in the study area, which is shown in the photo in Figure 2). In order to reflect a mature stand of native vegetation, the initial conditions were defined by the conditions in year-30 of Figure 6a, which had stocking levels defined as in Table 5.[18]

Figure 6: Carbon dynamics in newly established stand of *Tarchonanthus camphoratus*

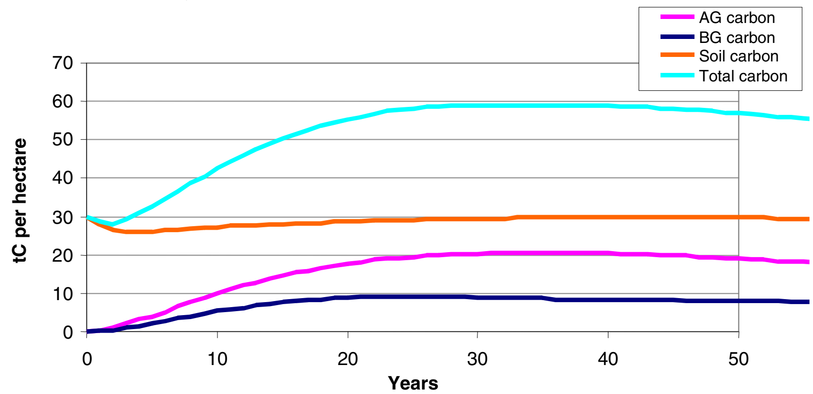


Figure 6b: Carbon dynamics in stand of *Tarchonanthus camphoratus* that is coppiced after 30 years

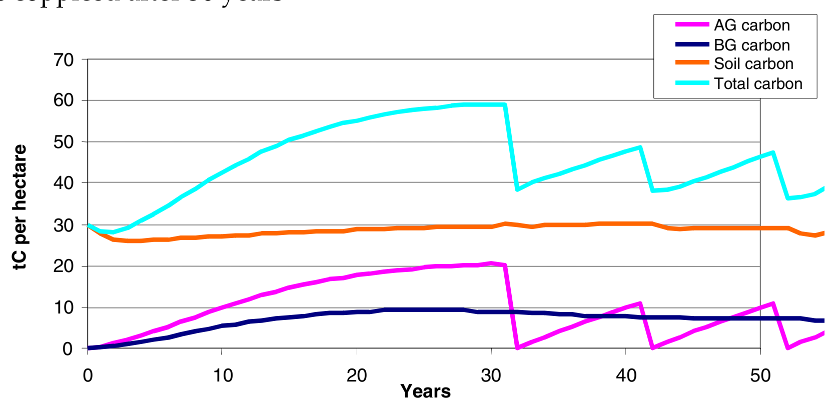


Table 5: Initial carbon stocks in stand of native vegetation (*Tarchonanthus camphoratus*)

Component	Carbon content (tC/ha)
Soil (carbon)	29.5
Biomass (carbon)	0
Stems	10.5
Foliage	0.3
Branches	9.6
Roots	9.1
Total	59.0

In each scenario, the stand was cleared for charcoal production in Year 1, after which management practices diverge as defined in Table 2. Each simulation is run for 50 years. The stocks of carbon estimated in each stand are shown in Figure 7. Over the 50-year simulation, the stands yield different quantities of charcoal depending on the length of the coppice cycle.

As is clear from Figure 7, each scenario results in different carbon dynamics. The initial conditions were defined by a mature stand of native vegetation. Hence, all but one of the scenarios result in a net loss of carbon in both biomass and soil because under coppice management, the stand never reaches the same level of biomass density it had when it was a "mature" stand. The only exception is the Eucalyptus coppice system, in which a fast growing species replaces relatively slow-growing native vegetation.

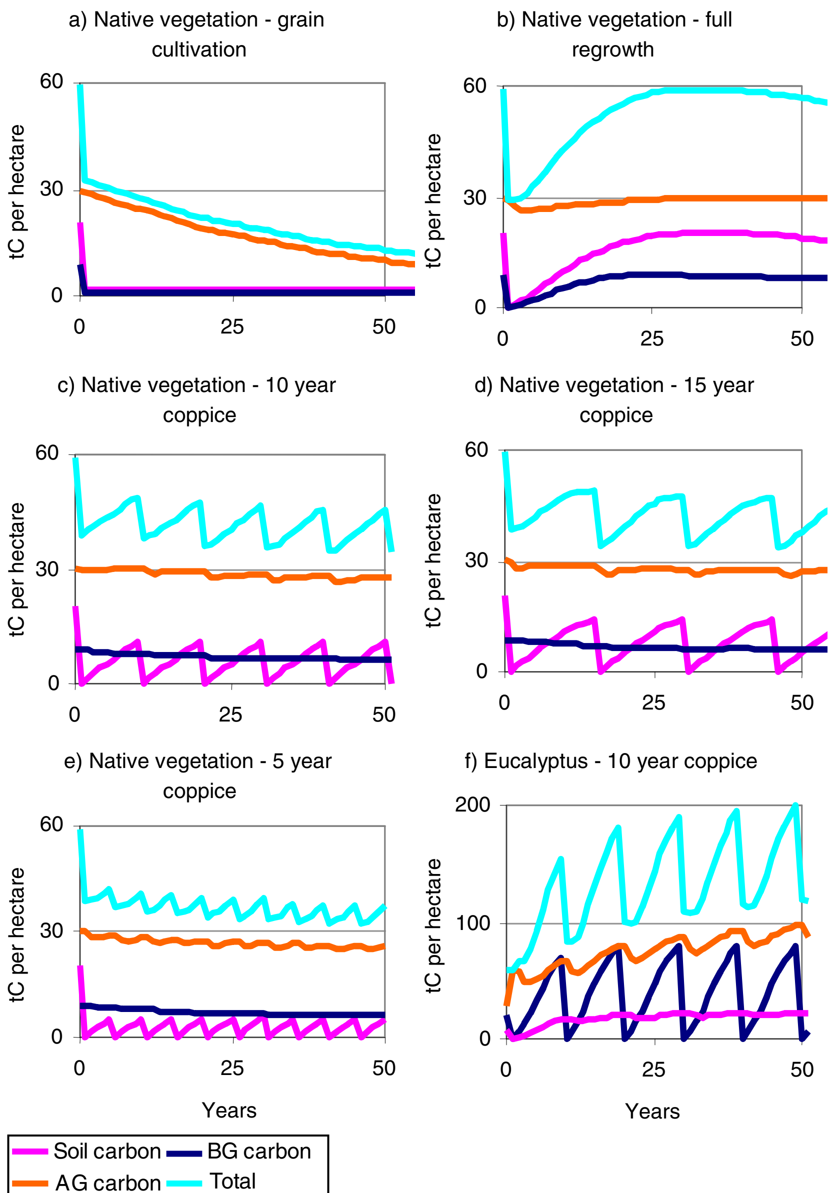
The top two graphs in Figure 7 (a and b) depict stands that are completely cleared for charcoal production including the removal of belowground biomass. In Figure 7, the area is plowed and cultivated with wheat, which is common in the study area. Crop cultivation not only results in the near-total loss of biomass; it also leads to substantial loss of soil carbon as a result of reduced litterfall and root turnover, minimal organic inputs, and repeated annual tillage.[19] In Figure 7 b, the area is allowed to regenerate naturally after clearance, which also occurs in the study area, though to a lesser extent. After roughly 50 years, both biomass and soil carbon have recovered their original levels. Figure 7c-f shows different types of coppice systems. Assessing changes in C in coppice systems should be approached carefully (Schlamadinger and Marland 1996). Rather than choosing a fixed time at which to assess net C-stocks, it is more appropriate to use a time average. A fixed time horizon only provides a snapshot into what is, in reality, a dynamic system; a time average provides a more accurate sense of the long-term implications of each management option. Average C-stocks are also sensitive to the choice of time horizon; however, the sensitivity is not as extreme as in the snapshot approach provided that sufficient coppice cycles are included. The results are presented in Table 6 with a 50-year time horizon.

Assessing the flux of carbon at this stage, prior to charcoal production, yields carbon emission factors that are solely dependent on land-use change. Summing the gain or loss in biomass carbon, soil carbon, and the net quantity of wood harvested as in equation 2, gives the total atmospheric flux of the system prior to the conversion of wood to charcoal. Taking the ratio of this quantity to the amount of charcoal produced from the harvested wood ΔC_p with efficiency ε gives an emission factor for land-use change (EF_{LUC}).

$$EF_{LUC} = -\left(\frac{\Delta C_b + \Delta C_s + \Delta C_p}{\varepsilon \, \Delta C_p} \right) \quad [4]$$

Fifty years after the initial clearance in the grain cultivation scenario there is a net flux to the atmosphere of 16.7 tC/ha. However, in each of the other scenarios, the combination of changes in biomass and soil carbon, together with harvested wood, result in a net sink of between 27 and 441 tC. Importantly, this only accounts for biomass, soil, and wood production and does not include emissions from the conversion of harvested wood to charcoal.

Figure 7: Carbon stocks in each stand of shrubs and eucalyptus*



*AG = above-ground; BG = below-ground

Table 6: Changes in carbon in each production system based on average C-stocks over a 50-year period [a]

	Initial C stocks			50-yr C stocks			Wood	Net C-flux	
Models	Bmass tC/ha	Soil tC/ha	Total tC/ha	Bmass tC/ha	Soil tC/ha	Total tC/ha	dry tons	ΔC_T tC/ha	EF_{LUC} [b] tC/ton_{charc}
Non-coppice systems									
Tarch grain	29	30	59	3	10	13	59	-16.7	1.14
Tarch regrowth	29	30	59	27	30	57	59	27.2	-1.85
Coppice systems									
Tarch5 coppice	29	30	59	10	27	36	128	41.4	-1.30
Tarch10 coppice	29	30	59	13	29	41	142	53.4	-1.51
Tarch15 coppice	29	30	59	14	28	42	121	43.1	-1.43
Euc coppice	29	30	59	56	76	132	736	441.1	-2.41

[a] A negative value for ΔC_T implies a net loss of terrestrial carbon. A negative value of EF_{LUC} implies a net sink of terrestrial C.

[b] EF_{LUC} is based on the conversion efficiency of earth-mound kilns (ε = 0.249).

Taking the ratio of ΔC_T to charcoal produced results in an emissions factor from land use change: EF_{LUC}. This is -1.14 for the clearance/cultivation scenario. The negative value reflects net loss of 1.14 tons of carbon to the atmosphere from biomass and soil for each ton of charcoal produced. For all other scenarios, $EF_{LUC} > 0$, reflecting a net sink of 1.30 - 2.41 tons of carbon from LUC for each ton of charcoal produced.

After the wood is harvested, it is cut to a manageable size and arranged for pyrolysis manually. Pyrolysis involves heating wood in the absence of sufficient air for full combustion to occur. This process releases the wood's volatile compounds and converts the constituents of wood (lignin, cellulose, and hemicellulose) into a relatively lightweight, clean-burning fuel that is 70-90% carbon (Foley 1986).

Charcoal can be produced by a range of methods, from simple earth kilns to brick or metal kilns as well as retorts that capture volatile compounds either for extraction or to use them as an additional source of heat to drive the charcoal-making process (FAO 1983; FAO 1985; Foley 1986).

Earth-mound kilns are the most common method of making charcoal throughout sub-Saharan Africa. A wide range of conversion efficiencies can be obtained from earth-mound kilns: between four and ten tons of dry wood may be required to make 1 ton of charcoal, which is a mass-based conversion efficiency of 10-25%. At these conversion rates, 60-85% of the wood's energy is lost in the production process. Using improved kilns or retorts can improve conversion efficiency and reduce energy losses to only 30 or 40% (see Appendix B). Improved kilns also result in lower GHG emissions. Figure 9 shows empirical measurements of emissions from different charcoal production technologies measured in several studies of earth-mound kilns in sub-Saharan Africa and improved technologies that are in use in Brazil. For the analysis in this study, emission factors from Kenyan earth-mound charcoal production were used to represent the traditional charcoal. Note, this plot only includes GHGs that are targeted for reductions in the Kyoto Protocol (KP) (IPCC 1997).[20]

Combining the emissions from LUC described in Table 6 with the emissions from charcoal production illustrated in Figure 9 gives the net emissions from both raw material extraction and fuel production. These are given in Figure 9 for both traditional (Kenyan earth-mound) and improved (Brazilian metal) kilns.

In the baseline (*Tarch grain*) case, charcoal made in both traditional and improved kilns result in net GHG emissions (1.9 and 1.1 tC per ton_{charc} respectively). However, in every alternate case, the regeneration of wood and retention of soil C cause the combined extraction and production stage to be a net sink.[21]

Figure 8: Upstream GHG emissions of household fuels: charcoal production measured in three Earth-mound kilns in sub-Saharan Africa and two improved kilns in Brazil (sources: Zambia (Bertschi, Yokelson et al. 2003); W. Africa (Brocard, Lacaux et al. 1996); Kenya and Brazilian improved kilns (Pennise, Smith et al. 2001; Pennise 2003)).

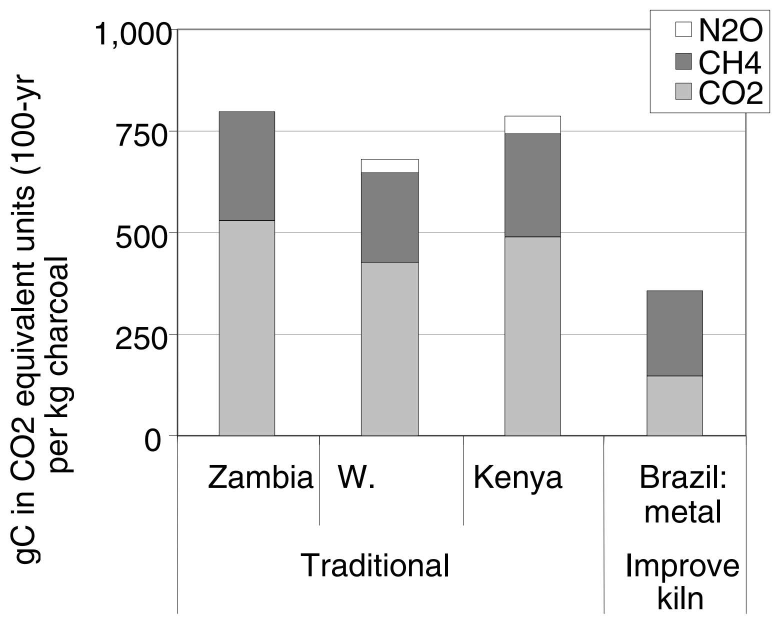


Table 7: Emission factors from wood extraction and pyrolysis (measured in tC/toncharc)

Models	EF_{LUC}	EF_{Prod}		EF_{LUC} + EF_{Prod}	
		Kenya EM	Brazil: metal	Traditional kiln (Kenyan)	Improved kiln (Brazil: metal)
Tarch grain	1.14	0.79	0.36	1.93	1.14
Tarch regrowth	-1.85	0.79	0.36	-1.06	-0.90
Tarch5 coppice	-1.30	0.79	0.36	-0.50	-0.53
Tarch10 coppice	-1.51	0.79	0.36	-0.71	-0.67
Tarch15 coppice	-1.43	0.79	0.36	-0.62	-0.62
Euc coppice	-2.41	0.79	0.36	-1.61	-1.29

Transmission/Distribution of wood and charcoal

In comparison to emissions from other stages of the charcoal life-cycle, emissions from transportation are fairly low. These were estimated using emission factors from the IPCC's Guidelines for National Greenhouse Gas Inventories (IPCC 1997). The IPCC offers a range of default emission factors reflecting different levels of emissions controls and fuel economy. The emissions factors used in this analysis assume the worst case scenario of no emissions controls and poor fuel economy (2.2 km/liter), which should accurately reflect the performance of vehicles used to transport fuels in Kenya.

Table 8: IPCC default emission factors for heavy duty diesel vehicles (in CO_2 equivalent units weighted by 100-yr GWPs) (IPCC 1997).

Quantity	Units	CO_2	CO	CH_4	NMHC (gC)	N_2O
Default pollutant emissions per unit distance	gC/km	299	3.9	0.3	4.5	9.3
Carbon emissions per ton of charcoal transported [a]	tC/ton	0.01	1 E-4	1 E-5	2 E-4	3 E-4
Carbon emissions per ton of LPG or kerosene transported [b]	tC/ton	0.04	3 E-4	3 E-5	4 E-4	7 E-4

[a] Each trip for charcoal covers a total distance of 300 km and carries 250 standard (35kg) bags of charcoal.

[b] Each trip for LPG or kerosene covers a total distance of 1000 km and carries 12,500 liters (10,000 kg) of fuel.

Summing the middle row of Table 8 yields a result that can be directly compared to the results from the previous stage of the charcoal life cycle. This indicates that transportation of charcoal from production site to market releases roughly 0.011 tC per ton of charcoal transported, which ranges from 1-3% of the various emission factors in Table 7. In any case, transportation plays a small role in charcoal's climate impact.

Consumption of wood and charcoal

Both wood and charcoal release GHGs when they are consumed in the household. Empirical studies show that between 4 and 15% of the fuel's carbon may be released as products of incomplete combustion(Brocard, Lacaux et al. 1996; Smith, Uma et al. 2000; Bertschi, Yokelson et al. 2003). Charcoal tends to be at the higher end of this range and fuelwood tends to be at the lower end. shows a range of empirical measurements of emission factors from the end-use of fuelwood and charcoal. As with production emissions, only KP GHGs are shown (see note above). Charcoal emission factors are systematically larger because they are defined per unit mass of fuel and charcoal has a higher carbon content than unprocessed fuelwood. For the remaining analysis in this paper, the EFs from Zambian study are used because they represent the median value among the three studies reported and no data on emissions from Kenyan charcoal end-use are available.

Summarizing the net emissions from wood and charcoal

Taking all of the emissions from the previous three sections together, we can estimate the net GWI for fuelwood and charcoal. These results are shown in Table 9. The table shows that the net emission factors for the charcoal life-cycle are highly dependent on the land management regime that is in place. For the baseline scenario, in which native vegetation is replaced by grain cultivation and charcoal is produced in a traditional earth-mound kiln, one ton of charcoal results in the release of over 2.7 tC over its entire life-cycle. However, if the cleared area is allowed to fully regenerate as in *Tarch regrowth*, the new growth of biomass more than compensates for the emissions from wood pyrolysis and fuel combustion, effectively sequestering ~0.26 tons of carbon after 50 years. If coppice management is practiced rather than allowing full regeneration, the overall system acts as a net source of carbon, but the emission factors are far smaller than that which results from full clearance, ranging from 0.08-0.29 tC per ton_{charc} depending on the length of the coppice cycle.[22] If natural vegetation is replaced by fast growing exotic species like *Eucalyptus grandis*, the increase in biomass that results acts as a sink of carbon, such that after 50 years of coppice management, roughly 0.8 tC are sequestered for every ton of charcoal produced.

Figure 9: Empirical measurements of emission factors from the end-use of fuelwood and charcoal (Brocard, Lacaux et al. 1996; Smith, Uma et al. 2000; Bertschi, Yokelson et al. 2003)

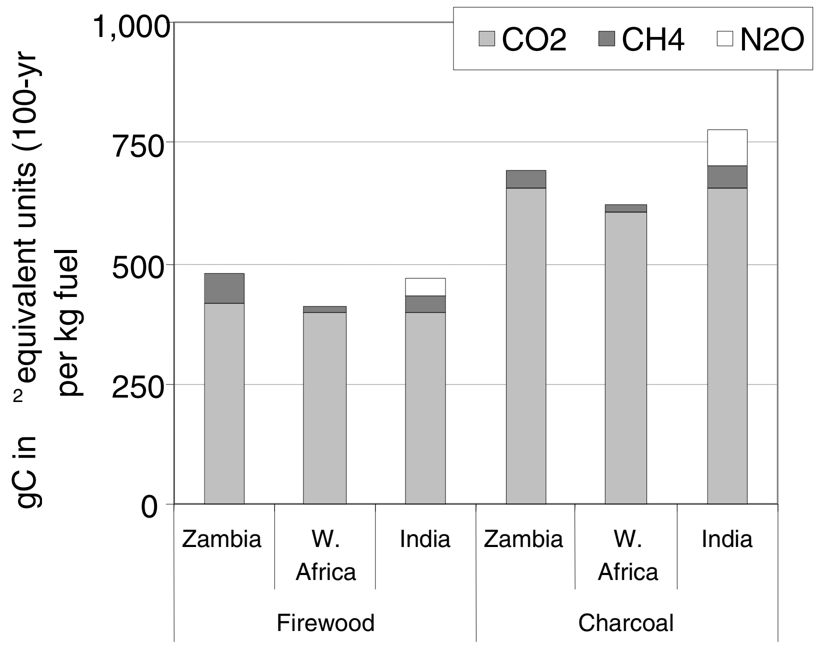


Table 9: Emission factors for wood and charcoal life cycles (tC per ton-fuel using only KP GHGs and 100 yr GWP)

	Raw materials extraction EF_{LUC}		Fuel production EF_{PROD}		Transport EF_{TRANS}	End-use EF_{CONS}	Total GWI EF_{TOTAL}	
	trad kiln	imp kiln	trad kiln	imp kiln			trad kiln	imp kiln
Fuelwood	--	--	--	--	--	0.06	0.06	--
Baseline								
Tarch grain	1.14	--	0.79	--	0.01	0.77	2.72	--
Alternates								
Tarch regrowth	-1.85	--	0.79	--	0.01	0.77	-0.26	--
Tarch5 coppice	-1.30	-1.03	0.79	0.36	0.01	0.77	0.29	0.26
Tarch10 coppice	-1.51	-0.98	0.79	0.36	0.01	0.77	0.08	0.11
Tarch15 coppice	-1.43	-1.65	0.79	0.36	0.01	0.77	0.15	0.17
Euc coppice	-2.41	-0.89	0.79	0.36	0.01	0.77	-0.82	-0.50

Using an improved kiln changes these results. An improved kiln is only feasible in the coppicing scenarios because, the charcoal is only made once on a given plot of land in the non-coppice scenarios, making investment in an improved kiln highly unlikely. When an improved kiln is used in the coppicing scenarios, it has a mixed set of effects. In the coppice systems LUC acts as a net sink ($EF_{LUC} < 0$). Thus, the use of the improved kiln actually raises EF_{LUC} because it raises the yield of charcoal from a given area of land. In addition, the improved kiln has lower EF_{PROD} than the traditional kiln, but EF_{TRANS} and EF_{CONS} are the same. The overall effect can either raise or lower the net emission factor, depending on the relative changes in EF_{LUC} and EF_{PROD}. The result is that EF_{TOT} for charcoal made from coppiced natural vegetation ranges from 0.11-0.26 tC per ton_{charc} and EF_{TOT} from coppiced *E. grandis* still reflects a net sink of -0.50 tC per ton_{charc}.

Wood is also included inTable 9. As discussed above, the only emissions we consider for wood arise from end-use. The value of

EF_{CONS} used here, 0.06 tC per ton_{wood} is derived from the non-CO_2 gases illustrated in Figure 9. CO_2 is omitted because it is assumed the wood is harvested sustainably so that CO_2 emissions are sequestered by new tree growth.

These results are illustrated in Figure 10. The figure shows the large difference in total emissions per unit of charcoal produced between land clearance for crop cultivation and land management for continual charcoal production.

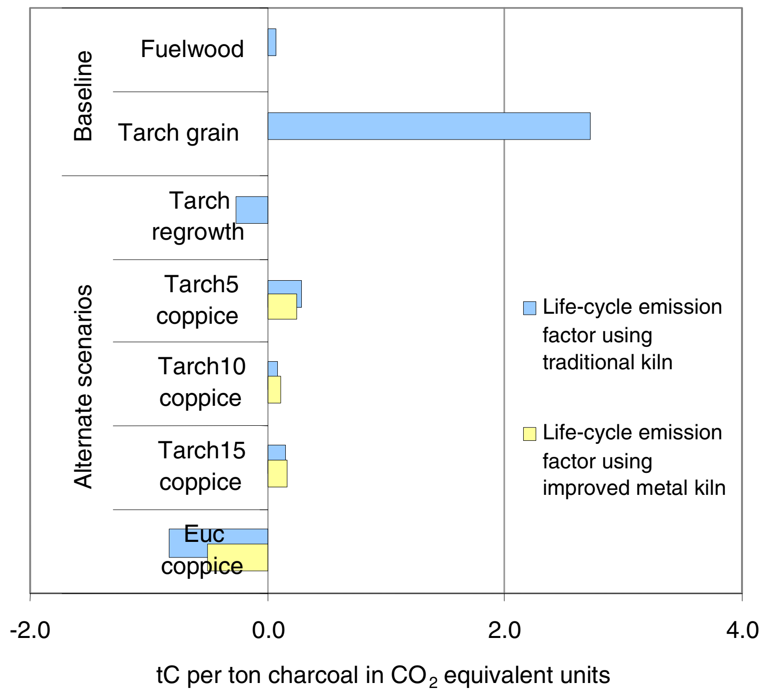
This concludes the analysis of GHG emissions from the fuelwood and charcoal life cycles. The next section will discuss the same for fossil fuels.

LPG AND KEROSENE

Raw material extraction and fuel production

Upstream activities resulting in GHG emissions in this stage of the fossil fuel life cycle include exploration, extraction, and refining as well as fuel transportation and storage. For this analysis, I used a software package was that estimates the sum of these emissions based on user inputs of refining efficiency, national electricity mix, transmission losses, as well as fuel transport methods and distances. The GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) was developed by Argonne National Laboratory as a tool to evaluate the climate impacts of the life cycle of transportation fuels in the US (Center of Transportation Research 2001).[23] As it was designed to evaluate transportation fuels, this model estimates “wells to wheels” emissions: i.e. from extraction to final consumption in a given vehicle. However, it is useful for this analysis because it disaggregates output into “wells to pump” and “pump to wheels”, thus it provides estimates of emissions for the raw material extraction and fuel production stage of the fossil fuel life cycle. The model’s output of “pump to wheels” emissions was simply discarded.

Figure 10: Emission factors for the fuelwood and charcoal life-cycle (tC per ton_{charc} in CO_2 equivalent units)



In addition, kerosene is not included as a fuel in the GREET model, as it is not used in vehicles. However, diesel fuel is part of the model. This analysis used diesel as a proxy for kerosene because it is a similar petroleum distillate, associated with similar upstream emissions (Pennise 2003). The model calculates emissions from LPG based on different sources of feedstock: crude oil or natural gas. Our model assumes LPG in sub-Saharan Africa originates from 100% crude oil.

Although it is designed to be used specifically for conditions in the United States, the model can be tailored to conditions in other places. For example, this analysis assumed that all of Kenya's LPG and kerosene are derived from imported crude oil. The oil is of Middle Eastern origin and is shipped entirely by oil tankers an average distance of 3,000 miles. The crude oil arrives at the port in Mombasa, where it is processed with 89% efficiency for diesel and 94% efficiency for LPG. The model is also tailored to Kenya's electricity mix, which was described in note b of Table 4. Figure 11 shows the emissions from raw material extraction and fuel production estimated by the GREET model.

Transmission/Distribution of LPG and Kerosene

After refining, the fuels are then transported to Nairobi (~500 km each way) by tanker trucks that hold roughly 12,500 liters (10,000 kg) of fuel. The result of these assumptions is shown in Table 8 above. Summing the relevant row of Table 8 shows that transportation of LPG and kerosene from Kenya's refinery in Mombasa to consumer markets in Nairobi releases roughly 0.025 tC per ton of fuel transported: roughly 20% of the emissions from raw material extraction and fuel production.

Consumption of LPG and Kerosene

Unlike solid fuels such as wood and charcoal, liquid and gaseous fuels are relatively easy to combust at the household scale. Thus, there are fewer pr oducts of incomplete combustion released by the end-use of LPG and kerosene. Figure 12 shows the emissions per unit mass of fuel consumed. Note the minimal release of methane, indicating much cleaner combustion than wood and charcoal depicted in Figure 9.

Figure 11: GREET model estimations of raw material extraction and fuel production emissions for LPG and kerosene.

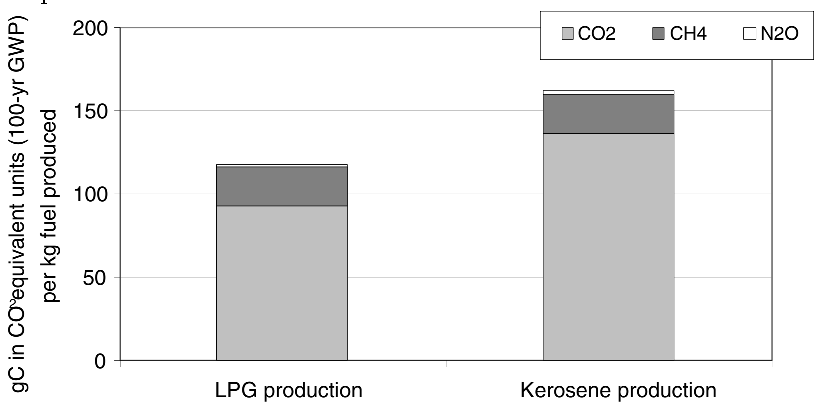
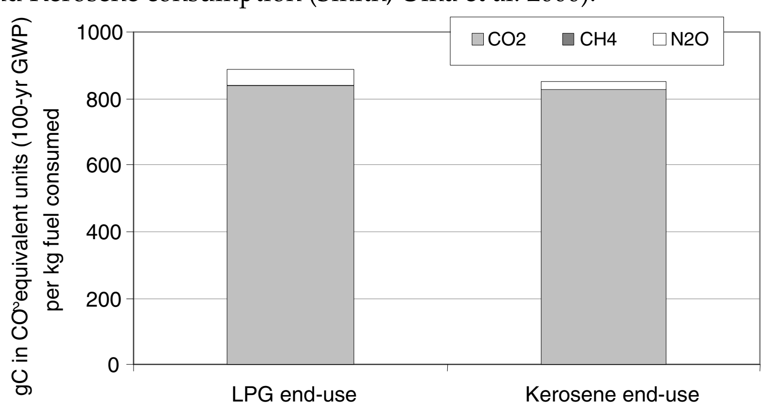


Figure 12: Empirical measurements of emission factors from the LPG and Kerosene consumption (Smith, Uma et al. 2000).



Summarizing the net emissions from LPG and Kerosene

Taking all of the emissions from the previous three sections together, we can estimate the net GWI for LPG and kerosene. These results are shown in Table 1.

Table 10: Emission factors for LPG and kerosene life cycles (tC per ton-fuel using only KP GHGs and 100 yr GWP)

	Raw materials extraction and production	Transport	End-use	Total GWI
	$EF_{LUC} + EF_{PROD}$	EF_{TRANS}	EF_{CONS}	EF_{TOTAL}
LPG	0.12	0.025	0.89	1.03
Kerosene	0.16	0.025	0.85	1.04

COMPARISON OF WOODFUEL AND FOSSIL FUEL LCA

Combining the results of the woodfuel and fossil fuel analyses provides a comprehensive view of the climate impacts from each household energy option. However, in order to compare the impacts of different types of fuels and stoves, it is more accurate to redefine the emission factors derived above factors based on *useful energy* rather than the mass of fuel produced and consumed. This accounts for higher calorific values and typical heat transfer efficiencies that liquid and gaseous fuels have relative to so lid fuels (Smith, Uma et al. 2000). The conversion factors are given below in Table 11 together with the net GWI on the basis of *useful* energy. The final results are also shown below in Figure 13.

Table 11: Calorific values, heat transfer efficiencies, and range of GWI for each form of household energy [a]

Fuel	Calorific value (Q) [b]	Heat transfer eff (η) [b]	$EF_{TOT-MASS}$ (tC/ton$_{fuel}$)	$EF_{TOT-ENERGY}$ (gC per *useful* MJ) [c]
Wood	16	15%	0.06	25
Charcoal – *Tarch grain*	31	25%	2.72	351
Charcoal – *Tarch regrowth*	31	25%	(0.26)	(34)
Charcoal – *Tarch coppice* (5-15)	31	25%	0.08 – 0.29	10-37
Charcoal – *Euc coppice*	31	25%	(0.82) – (0.50)	(106) – (65)
LPG	43	50%	1.03	48
Kerosene	46	54%	1.04	42

[a] Negative values of GWI represent net sinks and are given in parentheses ( ). Ranges for coppice systems include high and low values for the length of coppice and the type of kiln utilized.

[b] All data except charcoal are from the analysis in (Smith, Uma et al. 2000). The calorific value of charcoal is based on Kenyan charcoal analyzed in (Pennise, Smith et al. 2001) and the heat transfer efficiency of charcoal stoves is based on unpublished personal observations of Kenyan charcoal stoves.

[c] $EF_{TOTAL-ENERGY} = 1000 \cdot EF_{TOTAL-MASS} \cdot (Q \cdot \eta)^{-1}$

Figure 13: Net GWI for each stove-fuel combination on the basis of *useful energy*

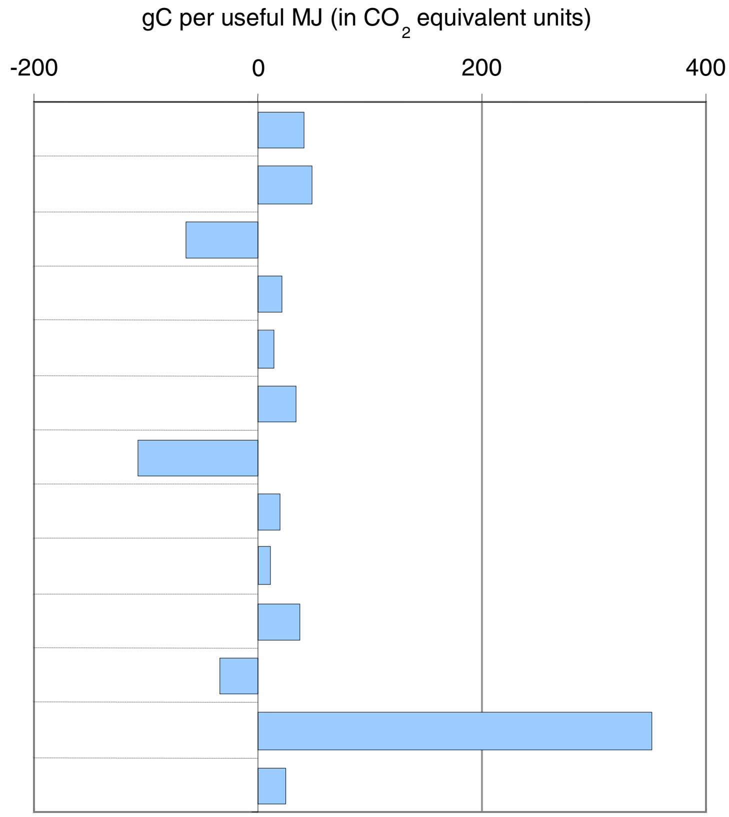


Figure 13 shows, on the basis of *useful* energy available to the end-user, the GWI of charcoal production accompanied by grain cultivation is nearly an order of magnitude larger than other household energy options explored here. In addition, because of higher calorific values and favorable heat transfer efficiency, the GWI of fossil fuels are within the same order of magnitude as the GWI from charcoal produced from native vegetation managed on 5, 10, or 15-year coppice cycles. It should also be noted that several options act as net sinks of carbon in this estimation.[24]

DISCUSSION

From these results, it is apparent that the net climate impacts of household energy use in Kenya and elsewhere in sub-Saharan Africa are strongly dependent on the management decisions that are made concerning the area in which charcoal is produced. The conversion of an area of woody savannah to grain cultivation results in the loss of roughly 40 tC per ha. Managing the same area of land by coppicing native vegetation on 5, 10, or 15 year cycles results in a net release of only 3-9 tC per ha with 30-35 tons of charcoal produced over a 50 year period. Replacing the area with a fast growing exotic species like *Eucalyptus grandis* can result in a sink of up to 150 tC per ha and over 180 tons of charcoal produced over a 50 year period.

There are many variables that affect land use in this region of Kenya, including socioeconomic factors like the demand for grain in rapidly expanding urban markets and changes in land tenure that enable land that was formerly under communal tenure and managed for pasture to be converted to farmland. In addition, land managers experience both threats and benefits from living in close proximity to wildlife, although the threats and benefits are mot necessarily distributed evenly among the population (Thompson and Homewood 2002). Finally, the degree of access that the land manager has to capital and markets for agricultural produce plays an important role. Not surprisingly, carbon management currently plays no role in land management decisions.

In Kenya there is pressure to expand crop cultivation as a result of growing demand for food. This should take precedence over carbon emissions. However, crop cultivation need not lead to the level of carbon loss that this analysis estimates is occurring in the study area. There are cultivation methods that are not currently practiced, which can reduce the loss of soil carbon (IPCC 1997). In the *Tarch grain* production system, changes in soil-C were responsible for about 50% of the net C reductions.

If we set aside issues of food security for a moment and just consider carbon dynamics and energy production, then, at a glance, it appears that the *Euc coppice* system is the best option for energy production. It is a large sink of carbon and yields the largest quantity of charcoal. However, several additional factors have been omitted from this analysis. These include the high costs of establishing a plantation and the high risk of failure for an exotic species. *Eucalyptus* spp. are susceptible to attack from termites and other local pests as well as sensitive to drought, which is a great concern in a drought prone area like the region under study.[25] In addition, even if it is commercially viable and risk can be properly managed, there are environmental considerations that may outweigh the benefits of carbon sequestration and increased charcoal production.

One such consideration is the hydrological impacts of replacing native vegetation with fast-growing tree species. In particular, *Eucalyptus* spp. have been maligned for their effects on local hydrological function. The degree of impact has been correlated with soil depth and water availability. Importantly, water use increases when plants are coppiced (Bruijnzeel 2004).

A second consideration is the effect that replacing natural vegetation has on biodiversity. While not as rich as tropical rain forest, woody savannah supports a range of flora and fauna. This region of Kenya is located adjacent to one of the largest concentrations of large herbivores in the world. It is less than 100 km north of the Maasai Mara National Reserve, which is itself contiguous with the Serengeti Plains in Tanzania. The area constitutes important grazing for wildlife that migrates north during the wet season in order to allow dry season pasture in the Serengeti-Mara Ecosystem to regenerate (Serneels and Lambin 2001). Since the mid-1970s, when grain cultivation was first introduced in the area, wildebeest populations have declined by 75%. If large areas are converted to fast growing plantations, it is likely to exacerbate this effect.

Managing natural woodland vegetation for continuous charcoal production is unlikely to have any negative impacts on hydrological function and is the land management option here that is most compatible with wildlife. In addition, there are no establishment costs for "natural plantations" and this option is effectively risk-free because natural vegetation is drought-tolerant and resistant to local pests. A landowner could manage 10 ha on a 10-year coppice cycle and earn an annual income that is competitive with the landowner who seeks to lease out the same land area for grain cultivation. The economics of the coppice management option become more favorable if land owners can be compensated for the carbon that would be released if they convert their land to grain cultivation. The economics of coppice management becomes still more favorable if land owners can be compensated for conservation, for example, through tourism revenue that flows to the local or national government, as well as for their carbon savings.

This analysis represents an initial investigation into alternative charcoal production systems in Kenya, where charcoal production to date has been closely associated with LUC and related negative environmental impacts. The economics of these systems remains to be fully explored, including possible revenue streams from carbon emissions reductions and conservation value in an area that is very close to highly valued wildlife habitat.

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APPENDIX A

Trees used for charcoal production in Narok District

	Local name [a]	Scientific name	No. of times mentioned in survey (n=50)	No. of trees/stems harvested during analysis of charcoal kilns (n=10)
1.	Leleshwa	*Tarchonanthus camphoratus*	20	215
2.	Olmusigiyioi	*Rhus natalensis*	8	32
3.	Olgilai	*Teclea nobilis*	3	3
4.	Mutamaiyu	*Olea africana*	10	3
5.	Oldaangutwa	*Pistacia aethiopica*	--	3
6.	Muthuthi	*Maytenus spp.*	--	2
7.	Oltepesi	*Acacia tortilis*	1	1
8.	Olkinyei	*Euclea divinorum*	4	1
9.	Olerai	*Acacia xanthaphloea*	6	--
10.	Olmorijoi	*Acokanthera schimperii*	3	--
11.	Olpelaglagi	*Trichocladus ellipticus*	5	--
12.	Eluai	*Acacia drepanolobium*	1	--
13.	Olmositet	*Celtis africana*	1	--
14.	Olsogonoi	*Warbugia ugandensis*	1	--
Total			63	260

[a] Local names are in Maa except *Mutamaiyu* and *Muthithi*, which are in Kikuyu (Beentje 1994).

APPENDIX B

Charcoal production efficiencies reported in previous studies and calculated in this study

Location	Kiln type	No. of kilns	Avg. eff. (%)	SD (%)	Comments and reference
Rwanda	Earth-mound	n = 47	8.2	3.0	2-15 m^3 input (ESMAP 1991)
Rwanda	Cassamance	n = 22	15.5	6.7	10-30 m3 input (ESMAP 1991)
Zambia	Earth-mound	n = 36	19.2	4.1	Inputs were all between 2.3 and 3.7 tons (dry basis) except for 3 trials which had over 10 tons each (Hibajane 1994)
Kenya	Small Earth-mound	n = 2	23.2	0.8	Inputs were all less than 1 ton (Pennise 2003)
Brazil	Round brick	n = 1	28.7	NA	Input was over 15 tons (dry wood) (Pennise 2003)
Thailand	Metal drum	n = 3	29.4	3.4	Inputs were very small (~60 kg dry wood) (Smith, Pennise et al. 1999)
Thailand	Earth-mound (rice husks)	n = 3	29.7	5.1	Inputs were rice husks between 100 and 200 kg (dry matter) (Smith, Pennise et al. 1999)
Thailand	Earth-mound	n = 3	29.8	2.5	Inputs ~170 kg (dry wood) (Smith, Pennise et al. 1999)
Thailand	Mud beehive	n = 3	30.8	1.3	Inputs were all roughly ½ ton (dry wood) (Smith, Pennise et al. 1999)

Location	Kiln type	No. of kilns	Avg. eff. (%)	SD (%)	Comments and reference
Kenya	Large Earth-mound	n = 3	32.8	3.3	Inputs were all larger than 10 tons (Pennise 2003)
Thailand	Brick beehive	n = 3	33.3	0.7	Inputs were roughly 0.7 tons (dry wood) (Smith, Pennise et al. 1999)
Brazil	Hot-tail	n = 1	34.1	NA	The hot-tail is similar to a brick beehive kiln with a moderate charge of ~3 tons (dry wood) (Pennise 2003)
Brazil	Rectangular metal	n = 1	36.4	NA	Kiln has tar recovery with very large inputs (> 60 tons dry wood) (Pennise 2003)
Kenya	Earth-mound	n =10	24.9	3.6	Inputs ranged from 1.2- 6.2 tons (dry wood) (this study).

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NOTES

[1] Mass conversion of charcoal typically ranges between 15 and 30 percent defined with respect to dry wood. Measurements conducted on 10 charcoal kilns during the course of this field work resulted in charcoal yields of 24.9 ± 2.7% (dry basis: mean ± 95% confidence interval).

[2] The contribution of charcoal to household income for charcoal makers is treated in a thesis chapter by the author that is currently under development.

[3] Following definitions used by the UN Food and Agriculture Organization (FAO), I use the term *fuelwood* to describe wood that is combusted directly for fuel (also commonly referred to as *firewood*). This is to distinguish fuelwood from wood that is carbonized to make charcoal, or processed in some other way before it is used as fuel. In contrast, the FAO uses *woodfuel* to describe any wood that is used for energy, including both *fuelwood* and wood that is transformed into charcoal before final use.

[4] Electricity is an important source of household energy, however few people have access to it. Moreover, there is evidence showing that when people in Africa do have access to electricity, they rarely use it for the bulk of their cooking needs, preferring to use it for lighting and running small appliances while using cheaper, low quality fuels for cooking and heating. In Kenya, roughly 15% of the population has access to electricity, but only 4% of the population use it for any cooking task, and less than 1% consider it their "main" cooking fuel (World Bank 2000; Bailis, Ezzati et al. 2005). Thus, in this analysis electricity will only be included in qualitative discussions, and will not be included in the quantitative comparisons of household fuel choice.

[5] This figure is derived from fieldwork conducted by the author. An explanation of the revenue streams associated with the charcoal

commodity chain is given in a thesis chapter that is currently in progress.

[6] The smoke produced by charcoal is lower than that produced by typical wood fires, however charcoal fires produce more carbon monoxide (CO) than wood per unit of fuel burned (Smith, Uma et al. 2000; Bhattacharya, Albina et al. 2002). This can lead to dangerous concentrations of CO in households using charcoal, although empirical measurements of pollution concentrations in households using wood and charcoal showed no significant difference in CO between the two groups of households (Ezzati, Kammen et al. 2000).

[7] See Appendix A for a list of tree species used for charcoal in the study area.

[8] Trust land is land that is occupied by rural communities, but administered by local government institutions (Okoth-Ogendo 1991). This should be distinguished from Group Ranches (see Table 1), which are essentially private lands held communally (Galaty 1980).

[9] In Kenya, there have been few systematic studies of stand-level impacts of charcoal production. One anecdotal account suggests that species distributions are impacted as a result of selective harvesting (Dodson 2002). Another study suggests that impacts are minimal if harvesting rotations are sufficiently long to allow for regeneration (Okello, O'Connor et al. 2001). Elsewhere in South and East Africa, several studies have been conducted that suggest the impacts of charcoal production are minimal if stands are well-managed (Chidumayo 1988; Chidumayo 1993; Hosier 1993).

[10] At the time of writing, there is one commercial firm in Kenya making charcoal on a large scale from *Eucalyptus spp*. using off-cuts and rejects from their production of utility poles (Mutimba and Matiru 2002). A second firm that used to extract tannins from plantation-managed *Acacia mearnsii* (black wattle) used to make charcoal from the remaining trees after the bark had been stripped. However, this company closed its operations and sold off its plantations several years ago (Nation Correspondent 1999; Nation Correspondent 2000).

[11] There is currently a new Forest Policy (Government of Kenya 2004) on the table that failed to pass a parliamentary vote in June, 2004, because of widely recognized political wrangling (Nation Team 2004). Although it is expected to eventually pass, it has yet to be brought up for a second vote.

[12] There are currently several pilot projects meant to demonstrate the feasibility of charcoal production from dedicated tree plantations for small, medium and large-scale farmers.

[13] The yields from earth kilns are highly variable. Appendix B lists charcoal yields from a range of previous studies as well as results from field work by the author.

[14] The social and political basis for subdivision is described in (Bailis 2005).

[15] This list is not meant to be exhaustive. See (Graedel 1998) for a more detailed description. Also, note that most of these "broad" environmental concerns overlap with one another in some way – for example, resource depletion and climate change.

[16] See (Smith, Uma et al. 2000) and (Bailis, Ezzati et al. 2003) for more detailed explanation of the derivation of emission factors.

[17] This model simulates stocks and fluxes of carbon in trees, soil, and products, as well as the financial costs, revenues and carbon credits that can be earned under different accounting systems. All outputs are simulated at the hectare scale with time steps of one year. In addition to the references listed, see http://www2.efi.fi/projects/casfor/ for a full description of the model, presentations, and examples of how the model has been applied.

[18] These levels coincide with typical conditions in woody savannah and shrubland. See {IPCC, 1997 #80;Breman, 1995 #34} for a full description.

[19] The assumptions used to quantify losses of soil-C in this scenario are derived from IPCC's Good Practice Guidelines (IPCC 2003).

[20] These gases are CO_2, CH_4, and N_2O. Other pollutants released by biomass pyrolysis and combustion also have an effect on the atmosphere's energy balance, including CO, NMHCs and PM. In addition, Figure 9 shows each GHG weighted by a 100-year global warming potential (GWP). The exclusion of non-KP gases and the choice of GWP affect the analysis.

[21] This result stands if either non-KP GHGs are included or if 20-yr GWP is used. However, it does not stand if both non-KP GHGs are included and 20-yr GWPs are used.

[22] See discussion in footnote 21.

[23] The author thanks David Pennise for directing him to this useful tool. Pennise was the first to use GREET in an analysis of life-cycle emissions from household fuels (Pennise 2003).

[24] It may be counter-intuitive that the *Tarch regrowth* management scheme acts as a net sink considering that 50 years after the initial harvest there is no increase in the stock of terrestrial carbon. However, in conducting a strict accounting of carbon stock and flows, it is apparent that a substantial amount of the carbon initially harvested does not enter the GWI calculus and is thus "sequestered" for the purposes of this exercise. For example, 1 (dry) ton of harvested wood contains ~0.48 tC. Converting this quantity of wood into charcoal in an earth-mound kiln yields roughly 0.24 tons of charcoal containing 0.20 tC with the remaining carbon released in a mix of solid, liquid and gaseous by-products. When the charcoal is then used for cooking, the emissions from final combustion combine with the by-products from pyrolysis. Based on empirical studies (Bertschi, Yokelson et al. 2003; Pennise 2003), the overall stream carbon in the by-products of the charcoal life cycle roughly consists of the following: 0.34 tC as CO_2, 0.05 tC as CO, 0.01 tC as CH_4, 0.02 tC as NMHCs, 0.02 tC as partially carbonized wood, 0.02 tC as condensable tars, and 0.02 tC as particulate matter. When only KP-gases are considered, only CO_2 and CH_4 are accounted for, leaving ~0.13 tC, over one quarter of the initial carbon quantity, seemingly "sequestered". Of course, much of this carbon is not effectively sequestered and some of the uncounted emissions, like CO and NMHCs, actually directly contribute to climate change. The "sink" observed here disappears if these gases are included.

[25] The area suffers drought roughly one out of every seven years. There is currently a pilot plot of *Eucalyptus spp.* that was established in the study area with donor support. It has just passed one year since planting and appears to be thriving with minimal management, however, it was established close to a perennial water source and requires occasional irrigation. It remains to be seen if this kind of activity will be possible without access to reliable water supplies and if it is a commercially viable venture.

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