Modeling climate change mitigation from alternative methods of charcoal production in Kenya

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Abstract

Current carbon accounting methodologies do not accommodate activities that involve emissions reductions from both land-use change and energy production. This paper analyzes the climate change mitigation potential of charcoal production in East Africa by examining the impact of changing both land management and technology. Current production in a major charcoal producing region of Kenya where charcoal is made as a by-product of land clearance for commercial grain production is modeled as the "business-as-usual" scenario. Alternative production systems are proposed based on coppice management of native or exotic trees. Improved kilns are also considered. Changes in aboveground, belowground, and soil carbon are modeled and two distinct baseline assessments are analyzed: one is based on a fixed area of land and one is based on the quantity of non-renewable fuel that is displaced by project activities. The magnitude of carbon emissions reductions varies depending on land management as well as the choice of carbonization technology. However, these variations are smaller than the variations arising from the choice of baseline methodology. The fixed-land baseline yields annualized carbon emission reductions equivalent to 0.5–2.8 tons per year (t y⁻¹) with no change in production technology and 0.7–3.5 t y⁻¹ with improved kilns. In contrast, the baseline defined by the quantity of displaced non-renewable fuel is 2–6 times larger, yielding carbon emissions reductions of 1.4–12.9 t y⁻¹ with no change in production technology and 3.2–20.4 t y⁻¹ with improved kilns. The results demonstrate the choice of baseline, often a political rather than scientific decision, is critical in assessing carbon emissions reductions.

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1. Introduction

This paper models carbon dynamics of charcoal production in order to quantify the greenhouse gas mitigation potential of the charcoal trade in Kenya. In many African countries, charcoal constitutes a major source of greenhouse gas (GHG) emissions [1]. Like in any bioenergy system, carbon dynamics from charcoal are linked to two distinct processes: terrestrial carbon dynamics and emissions from fuel processing and combustion. Consequently, the degree to which the charcoal industry can contribute to climate change mitigation depends on land use as well as energy conversion technologies. The dual components of the baseline complicate assessments of emissions reductions (ERs) that result from changing production practices. I analyze charcoal as it is current production in one part of Kenya and model several alternative production methods that have been proposed in order to promote sustainable production [2–5].

Estimates of Kenya’s charcoal consumption vary widely (Fig. 1), but it is likely one of the largest charcoal consumers globally in absolute and per capita terms [1,6,7].
The majority of the country’s charcoal originates in woody savannah that constitutes over two-thirds of the country’s area [5,8,9]. Woody savannah is a resilient ecosystem [10,11], which can recover from charcoal production under some management regimes [12–14]. When charcoal production contributes to long-term deforestation, it is typically the result of post-harvest management decisions. If trees cover is re-established, emissions are reduced relative to the deforestation scenario. However, emissions are not entirely negated because charcoal production releases 2–3% of the tree’s carbon as CH₄, which has nine times the warming impact of a molar equivalent quantity of CO₂, and a small quantity of N₂O, an even more potent GHG [15–19].

The degree of post-harvest tree regeneration depends on environmental as well as socioeconomic factors, which are mediated by environmental regulations that might be set at a national or sub-national level. In Kenya, such regulations do not favor sustainable charcoal production [20].

The Clean Development Mechanism (CDM) of the Kyoto Protocol is the primary vehicle through which climate change mitigation projects are developed. “Traditional” forms of bioenergy are largely absent from the CDM. To date, two methodologies involving charcoal production have been approved by the CDM Executive Board (the approved methodologies are AM41 and AMS-III.K: see [21,22]). Each one calculates emission’s reductions based on reductions in CH₄ induced by changing charcoal production technology. Neither makes an attempt to assess carbon flux resulting from LUC [23].

However, methodological difficulties arise as a result of the need to account for land-use change (LUC) and energy-related emission reductions within a single project. To reduce uncertainties, the CDM-EB defines biomass as either renewable or non-renewable. Their classification includes woody and non-woody biomass from forested and non-forested land as well as biomass wastes. Woody biomass originating from forestland is the most appropriate for analysis of existing charcoal production systems. In this context, biomass is renewable if [24]:

1) the land remains a forest;
2) sustainable management practices are in place to ensure that the level of carbon stocks does not systematically decrease over time (stocks may temporarily decrease due to harvesting); and
3) all national or regional forestry and nature conservation regulations are complied with.

Biomass that fails to meet all three conditions is “non-renewable biomass” (NRB) by default.

This paper proceeds as follows. Section 2 examines some of the methodological challenges that arise when analyzing the carbon implications of a shift from NRB to sustainable biomass. Section 3 describes the charcoal production systems currently used in Kenya and several alternatives to this system. Section 4 introduces the model used to estimate GHG emissions from different charcoal production systems. Section 5 presents the results and Section 6 discusses the policy implications and suggests some possible paths for future research.

2. Methodological issues in LUC and bioenergy

The analysis relies on CO2Fix (version 3), a “carbon bookkeeping” model (additional details are provided below, but also see [25–27]).

Greenhouse gas (GHG) emissions from charcoal result from three distinct processes: LUC processes induced by wood harvest, pyrolysis of the woody feedstock; and the combustion of the charcoal itself. Several studies have quantified emissions from both pyrolysis and end-use [18,28–31]. However, there have been few analyses of the impact of the charcoal economy on land cover, nor the effect of changes in charcoal production technology. Others have assumed a fixed percentage of biomass regenerates, but with little empirical basis [1]. These approaches do not accurately assess carbon dynamics at the stand level. In addition, none of the studies conducted to date have considered soil carbon, which is likely to change in response to LUC.

Additional approaches carbon dynamics in wood fuel systems have utilized GIS models to identify imbalances between wood fuel supply and demand [32,33]. At the stand level, several empirical studies have measured biomass regeneration in stands of trees harvested for charcoal production [13,14,34,35]. Other researchers have modeled stand-dynamics in fuel wood systems to estimate carbon flux, including changes in carbon stored in the soil and in forest products [26,36,37]. However, to date none have modeled carbon dynamics in charcoal production systems.

In any bioenergy system, emission reductions are sensitive to the choice of the “functional unit”, a concept commonly deployed in life-cycle assessment in order to systematically define the performance of a good or service [38]. Characterizing the functional unit in bioenergy systems in the context of GHG abatement is challenging because LUC must be accounted for
in parallel with emissions from processing and end-use. For LUC activities, it is logical to assess changes in carbon stocks in biomass and soil from a fixed area of land (e.g. 1 ha). Emissions that result from processing harvested wood from that land area are also accounted for. Thus, emissions from LUC and processing attributable to the “functional unit” are summed and compared to the “business-as-usual” (BAU) scenario, accounting for “leakage” if applicable (see [39] and the discussion in Section 6 below). However, when an activity induces a shift away from NRB, it is logical to account for emissions reductions based on a “functional unit” of energy delivered to consumers. Indeed, the methodologies that the CDM-EB approved for NRB substitution bases its assessment of emission reductions on “the fuel consumption of the technologies that would have been used in the absence of the project activity times an emission coefficient for the fossil fuel displaced,” [39]. This raises challenging questions because different emission reductions result from the choice of functional unit as unit of land or energy.

3. Charcoal production systems

3.1. Charcoal production technology

Charcoal can be made from many forms of biomass, including agricultural residues and timber waste [40]. However, nearly all charcoal in Kenya is made from native woody vegetation [4,8]. Survey results show over 200 different tree species are used [5,9,20]. Indigenous trees are favored, though in certain areas exotic trees are also used [41–43].

Pyrolysis takes place in an enclosed space, ranging from a simple pit or earthmound (EM) kiln to brick or metal kilns. In industrialized settings, retorts may be used, which utilize combustible compounds in the wood to generate heat for pyrolysis [44,45], but retorts have not been used in Kenya. EM kilns are typically thought to have low yields, although empirical measurements show that yields, while variable, can overlap with yields from improved kilns. For example,

Fig. 2 – Charcoal and carbon yield from earthmound (EM) and improved kilns reported in published literature. Charcoal yield is defined as the mass of charcoal to the mass of dry wood used as feedstock. Carbon yield is defined as the mass of carbon in the charcoal to the initial mass of carbon in the wood. * (Sources: kilns in Brazil [17]; Large and small kilns in Kenya [17]; Medium kilns in Kenya [20]; Thailand [31]; Zambia [47]; and Rwanda [49]. In studies reporting both mass and carbon yields, there is only moderate correlation between the two variables ($r^2 = 0.64$), indicating that the degree of pyrolyzation likely differed).
in Kenya, government literature cites yields of just 10% (mass basis) [4]. However, fieldwork by this author and others finds mass-based yields from EM kilns as high as 20–30% [30,46–49].

Yield is typically defined as the ratio of charcoal produced to dry wood input. However, comparisons between different studies should be made with caution as methodologies vary. In addition, this definition of yield doesn’t account for the degree of carbonization that the wood has undergone. High temperatures and/or long residence times in the kiln yield charcoal with a higher fraction of fixed carbon and lower content of volatile matter, which lowers the mass of the end product, but does not necessarily reduce the thermodynamic efficiency of the process [50]. Thus, conversion efficiencies are hard to interpret without information about the extent of carbonization. Nevertheless, Fig. 2 is included here to show the range of efficiencies reported in the literature. Notably, two studies measured carbon yield and both mass and carbon yields from these studies are shown.

Traditional kilns are favored across sub-Saharan Africa because they require very little capital investment, are flexible in size and shape, and are well-matched to the dispersed nature of the charcoal trade [5]. Measurements from charcoal production show overlap in emissions from EM and improved kilns. EM kiln emissions range from 0.514 to 0.840 t C (in CO₂ equivalent units weighted by 100 y global warming potentials) per ton charcoal. Emissions from improved kiln technologies vary from 0.400 to 0.820 t C per ton charcoal (Fig. 3).

This analysis relies on data from Kenya to estimate EM emissions [30]. For the improved kiln, emissions from a Brazilian metal kiln are used [30]. This is the cleanest production technology reported and was chosen in order to show the

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**Fig. 3** – Emissions measured in traditional earthmound (EM) kilns and a variety of improved kilns reported in the literature showing emissions of each GHG weighted by its 100-year global warming potential. Arrows indicate the emissions factors used in this analysis. * [* Non-CO₂ gases are expressed in CO₂-equivalent units using 100-year global warming potential (GWP), a dimensionless factor that expresses the warming impact of GHGs relative to the warming impact of CO₂ [68]. Sources: emissions from Brazil and Kenya [17]; emissions from Thailand [31]; emissions from Zambia [28]; and emissions from W. Africa [29]. Reference [28] found N₂O levels very close to detection limits and do not report an emission factor.**

**Fig. 4** – Land-use change model for estimating emissions from wood harvesting - adapted from [25].
largest possible contrast between technical options. In reality, this option would likely be too costly for local production, although it is possible that a scaled-down more locally appropriate version could be developed.

3.2. Land management

There are two dominant modes of charcoal production in Kenya and a third mode that is proposed, but not practiced: 1) charcoal as a by-product of land conversion from woodland to cropland, 2) charcoal produced on Kenya’s semiarid rangelands without conversion to cropland and 3) management of either natural woodlands or plantations for sustained charcoal production.

Historically, much of Kenya’s charcoal production has been linked to agricultural expansion [4]. When woodlands are converted to croplands, there is a long-term loss of terrestrial carbon and a reduction in soil carbon, as inputs of carbon from leaf litter and decaying biomass are reduced and soils are subject to annual tillage. This loss occurs whether or not charcoal is produced because in the absence of charcoal production trees are cleared and probably burned in situ. However, the warming impact may be greater with charcoal production because the GHG emission factors per ton of standing biomass are greater when charcoal is produced than when woodlands are burned [28].

In other modes of charcoal production, the loss of terrestrial carbon may be temporary. In Kenya’s rangelands, trees are harvested with little post-harvest management. Many species can coppice and, left undisturbed, cleared woody savannah typically regenerates [13,14]. However, regeneration is contingent on natural and anthropogenic factors including the presence of wildlife and livestock, precipitation patterns, soil qualities, and natural or anthropogenic burning [11,51].

The net change in terrestrial carbon stocks on woodlands composed of either exotic or indigenous tree species, when managed for charcoal will depend on both the frequency of harvest, and the management applied. This study analyzes six charcoal production scenarios drawn from the three modes of production. The business-as-usual (BAU) scenario simulates current charcoal production in Narok District (1°5′South, 35°52′East), where the author conducted extensive field work in 2004 and 2005. At the time, Narok was a major charcoal supply zone, providing roughly 30% of Nairobi’s charcoal [20]. Charcoal in Narok originates in woodlands dominated by *Tarchonanthus camphoratus*, a common dioecious evergreen shrub. It is usually multi-stemmed, growing up to 9 m, with a sparse crown and a trunk up to 40 cm in diameter. It favors dry forest margins or secondary woodlands and is often dominant or co-dominant in association with *Acacia* spp. [52,53]. In the BAU scenario, a full-grown stand of native vegetation is completely cleared (including all aboveground (AG) and a large portion of belowground (BG) biomass). Charcoal is produced from the cleared biomass and wheat is planted on the cleared land. A variation of BAU with an improved kiln is included to demonstrate the effect of a technological shift with no change in land management.

Additional scenarios are explored in which improved kilns and coppice management of either native vegetation (assumed to be pure stands of *T. camphoratus*) or a common exotic species (*Eucalyptus grandis*) are introduced. Table 1 describes each scenario in more detail.

### Table 1 – Baseline and alternative models of charcoal production.

<table>
<thead>
<tr>
<th>Model name</th>
<th>Land management model</th>
<th>Initial harvest</th>
<th>Key assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline-EM</td>
<td>Clearance of native vegetation (AG and BG) via one-time charcoal production in a traditional EM or improved kiln followed by wheat cultivation</td>
<td>All AG and 50% of BG biomass is cleared, initial soil carbon is lost due to annual tillage so that 36% of initial soil-C is lost after 20 years.</td>
<td><em>a</em> This matches the IPCC’s default assumptions for conversion of woodlands to croplands [57, Ch. 3].</td>
</tr>
<tr>
<td>Baseline-IK</td>
<td>via coppice management of native tree cover on 5, 10, and 15-year coppice cycles with harvested wood processed in EM or improved kilns, depending on the scenario.</td>
<td>All AG biomass, BG biomass is left intact</td>
<td></td>
</tr>
<tr>
<td>Tarch5-EM</td>
<td>Clearance of native vegetation (AG only) for charcoal production in an EM kiln followed by coppice management of native tree cover</td>
<td>All AG and 50% of BG biomass is cleared</td>
<td></td>
</tr>
<tr>
<td>Tarch10-EM</td>
<td>on a 10-year cycle with harvested wood processed in EM or improved kilns, depending on the scenario.</td>
<td>Coppiced stands regenerate without loss for entire modeling period. Growth of AG biomass during coppice cycles is boosted by 5% relative to growth from seed due to intact root structure.</td>
<td></td>
</tr>
<tr>
<td>Tarch15-EM</td>
<td></td>
<td></td>
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<tr>
<td>Tarch5-IK</td>
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<td>Tarch10-IK</td>
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<tr>
<td>Tarch15-IK</td>
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<tr>
<td>Euc10-EM</td>
<td>Clearance of native vegetation (AG and BG) for charcoal production in an EM kiln followed by coppice management of <em>E. grandis</em> on a 10-year cycle with harvested wood processed in EM or improved kilns, depending on the scenario.</td>
<td></td>
<td></td>
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<tr>
<td>Euc10-IK</td>
<td></td>
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</tbody>
</table>

### 4. Estimating emissions from charcoal production

#### 4.1. Modeling terrestrial carbon dynamics in charcoal production systems

CO2FIX (Version 3.1) was used to estimate terrestrial carbon dynamics in each wood fuel production system. The total stock of carbon at time $t$ is the sum of carbon in three pools:

$$ C_{T}(t) = C_{ag} + C_{bg} + C_{pt} $$

$t$ defines an increment of time, $C_{T}$ is the total stock of carbon, $C_{ag}$ is the carbon stored in AG and BG biomass, $C_{pt}$ is the carbon stored in soil organic matter, and $C_{pt}$ is the carbon stored in soil organic matter.
forest products. In this case, charcoal is the only product, and it is consumed in the same period as the harvest. All carbon stocks are measured in tonne per hectare. The model treats each component as a separate module that is parameterized independently. A diagram of stocks and flows of carbon is shown in Fig. 4; modules are distinguished by broken gray lines.

From one time period to the next, carbon flows within and between modules as depicted by the arrows in Fig. 4. After a time period of $n$ years, the net flux of carbon can be determined by summing the difference in each module between $t = n$ and $t = 0$:

$$
\Delta C_T = C_{Tn} - C_{T0} = \Delta C_b + \Delta C_s + \Delta C_p
$$

$$
= (C_{bn} - C_{bo}) + (C_{sn} - C_{so}) + (C_{pn} - C_{po})
$$

(2)

To simulate carbon dynamics for a given stand of trees, each module must be parameterized according to the physical properties of the stand. Parameterization is described below.

### 4.2. Biomass

The biomass module is parameterized with a biomass growth function with branches, foliage and roots defined relative to the stem. In addition, the turnover of each component must be defined as well as wood density, carbon content, mortality, and harvest-induced losses.

Each scenario has identical initial conditions, defined as a mature stand of *T. camphoratus*, which is assumed to have a total terrestrial carbon content of $\sim 60 \text{ t ha}^{-1}$ apportioned with roughly 35% in AG biomass, 20% in BG biomass, and 45% in the soil. Table 2 shows estimated carbon allocation in the initial plot. This allocation of soil and biomass carbon matches the typical range for savannah woodlands where “root-to-shoot ratios” of 0.5 are common [11,54]. Model parameters also match empirical data for *T. camphoratus* measured by Young and Francombe [35] in coppiced stands. That study found a mean annual increment (MAI) of 2.3 dry t ha$^{-1}$ after 6 years of regeneration. The growth function used in this analysis simulates their findings: the MAI is 2.3 t ha$^{-1}$ after six years, increasing to 3 t ha$^{-1}$ at 20 years and then declining to simulate slowing growth of a mature stand.

To simulate growth of *E. grandis*, a growth function based on in an ecological zone similar to the study area in Kenya was used [55]. Two site quality (SQ) indices were chosen in order to simulate two rates of tree growth (moderate and slow). Both are managed on a 10-year rotation. The growth functions (current annual increments (CAI) and mean annual increment) used for both species are shown in Fig. 5.

### 4.3. Soil

The soil module incorporates a soil carbon model that has been shown to robustly estimate decomposition rates for different types of litter across a range of climates [56]. The model assumes carbon inputs to the soil via three litter compartments: coarse consisting of stemwood, fine consisting of branches and coarse roots, and non-woody consisting of foliage and fine roots. The rate of carbon input into each compartment is determined by the growth and turnover rates, as well as inputs arising from mortality and slash (defined in the biomass module). Depending on its chemical composition, litter is partitioned into one of three subsequent compartments: soluble compounds, holocellulose, and lignin-like compounds. In addition to these compartments, there are two

![Fig. 5 - Current and Mean Annual Increments (CAI and MAIs) for a pure stand of T. camphoratus as well as moderate and slow-growth stands of E. grandis. Initial years of T. camphoratus are based on empirical observations [35]; the later years are estimated in order to give maximum AG carbon of $\sim 25 \text{ t ha}^{-1}$. Growth curves for E. grandis are based on empirical data from South Africa [55].](image-url)
humus compartments, which receive inputs from the coarse woody litter as well as the faster decomposing compounds. The model applies temperature- and moisture-dependent rates of partitioning and decomposition that have been calibrated across a range of temperatures [56].

For this analysis, the soil module was parameterized such that initial soil carbon is roughly 30 t ha\(^{-1}\), which is the low end for the range observed in savannah woodlands but is well-matched to the steady state of carbon that would result from leaf litter and root turnover of *T. camphoratus* as well as local temperature and moisture conditions. The IPCC lists approximate soil organic carbon under native vegetation in dry tropical regions (rainfall less than 1000 mm y\(^{-1}\)) between 35 and 60 t y\(^{-1}\) [54,57]. Ringius [58] notes soil carbon ranged between 30 and 44 t ha\(^{-1}\) in several different soil types in different locations in Kenya prior to crop cultivation [59].

### 4.4. Forest products

The product module tracks the carbon in the harvested wood. In the case of stands that are managed strictly for woodfuels, there are no long-lived products. All fuel-bound carbon extracted in a given period is released to the atmosphere immediately.

### 4.5. Adjusting the model for coppice systems

CO2Fix is not designed to calculate carbon dynamics under coppice management. The model assumes that biomass either enters the pool of wood products or litter upon harvest whereas under coppice management, BG biomass remains in the pool of living biomass. Moreover, because there is already a well-established root system, early stem growth in subsequent generations is typically faster than stem growth in trees planted from seed or seedlings [60,61].

Coppicing was simulated by using BG biomass and soil-C at end of the nth coppice cycle to define the initial BG and soil conditions for the \((n+1)\)th cycle. Lettens and colleagues describe an alternate approach for dealing with coppicing within CO2Fix [37].

### 5. Results

#### 5.1. Emissions reductions from carbon storage

In each scenario, a mature stand of *T. camphoratus* is cleared for charcoal production in order to reflect current practices in

![Fig. 6 – Carbon stocks in each stand of *T. camphoratus* and *E. grandis*.](image)
the study area. This initial clearance is defined as Year-1. Subsequently, management practices are defined as in Table 1. Each simulation was run for 30 years (the maximum lifetime of an A/R project in the CDM). The evolution of carbon stocks is shown in Fig. 6a–f.

The two E. grandis scenarios, which have peak growth rates four and seven times larger than the peak growth rate of T. camphoratus respectively, have vertical scales that are double the stands of T. camphoratus. Fig. 6a shows the baseline scenario, in which initial AG and BG biomass are harvested. After harvest, stocks of living biomass drop to near zero and the soil receives a pulse of carbon in the form of fine roots and leaf litter. Soil carbon decays rapidly at first, then more slowly as carbon is shifted to longer-lived pools in the soil. Wheat is cultivated during the entire period, creating small stocks of biomass carbon during each growing season. This is estimated at roughly 2 t ha⁻¹ based on average wheat yields in Narok district (3.3 t ha⁻¹ [62]) and published estimates of stalk to grain and root-to-shoot ratios in wheat [57, Ch. 4].

Fig. 6b–d show the simulations for each stand of T. camphoratus. Carbon is lost relative to Year-0 because the trees never reach the size of the mature stand. The models also show gradual declines in BG and soil carbon during the modeling period, because natural turnover of the fully formed roots outpaces the ability of the tree, with smaller quantities of AG biomass, to allocate BG carbon. Inputs of leaf litter are also lower than in the mature stand of trees. These declines are most pronounced in the 5-year coppice cycle. Fig. 6e and f show slow and moderate rates of growth for E. grandis under a 10-year coppice cycle. Stocks of carbon in AG and BG biomass are far larger than in T. camphoratus scenarios. In addition, soil carbon increases over time because leaf litter and root turnover are larger in stands of E. grandis.

5.2. Emissions from charcoal production

Total quantities of charcoal produced in each scenario are shown in Fig. 7. Emission factors given in Fig. 3 are multiplied by charcoal production in each scenario to define emissions from pyrolysis (shown in Table 3).

<table>
<thead>
<tr>
<th>Table 3 – Carbon emissions from pyrolysis after 30 years of charcoal production on each hectare of land (t ha⁻¹ in CO₂ equivalent units using 100-year GWPₚ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
</tr>
<tr>
<td>Tarch5</td>
</tr>
<tr>
<td>Tarch10</td>
</tr>
<tr>
<td>Tarch15</td>
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<tr>
<td>Euc (slow)</td>
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<tr>
<td>Euc (moderate)</td>
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</tbody>
</table>

5.3. Assessing changes in carbon stocks relative to the baseline

Each emissions profile can be assessed at the stand level assuming a fixed land area. Carbon stocks at each point in time are subtracted from the carbon stocks in the baseline. This yields time-dependent emission reductions for each scenario, shown in Fig. 8a and b. The plots extend to year-31 to show the effect of a final harvest on carbon dynamics in each scenario.

The net change in carbon closely mirrors the coppice cycle. However, peak carbon storage declines over time as a result of successive cycles of charcoal production. Each time charcoal is produced, CH₄ and N₂O are released, which are not fully offset by the next cycle of biomass growth. Thus, with each successive cycle of charcoal production, the net sequestration relative to the baseline is diminished. This effect is more pronounced in Fig. 8a, which shows the results for EM kilns, because more CH₄ and N₂O are released per unit of charcoal produced.

Fig. 9 shows changes in carbon stocks and emissions from charcoal production relative to the baseline scenario after 30 years of management.
years of management. Stock changes are shown for each pool (AG, BG, and soil). Emissions are shown for both EM and IK scenarios. Simply shifting to an IK with no change in post-harvest management results in carbon emission reductions of 3.4 t ha$^{-1}$. Shifting to coppice management and using an EM kiln reduces carbon emissions by 20–105 t ha$^{-1}$. Shifting to IK production yields reduces carbon emissions by an additional 4.4–21.4 t ha$^{-1}$. Averaged over the 30-year project lifetime, these scenarios generate annual carbon offsets ranging from 0.1 to 3.5 t ha$^{-1}$. For comparison, the median annual carbon offsets among the 30 afforestation/reforestation projects currently in the CDM pipeline is $\sim 3$ t ha$^{-1}$ [23].

As discussed above, quantifying emission reductions based on the amount of energy from NRB that is displaced gives a different picture. Coppice management yields 1.6–14 times the amount of deliverable energy per hectare relative to the baseline scenario. Thus, to deliver the same quantity of charcoal as in the coppice management scenarios, additional land must be cleared. Fig. 10 shows the results of adding additional land. Here, net emission reductions and carbon sequestered increase by 150–500% relative to the fixed land scenario. Further, shifting from EM to improved kilns increases the net emission reductions and sequestered carbon by an additional 60–120%. Table 4 summarizes the average annual carbon savings achieved by each scenario under the two baselines.

### 6. Discussion

This analysis demonstrates that GHG emissions reductions can be realized by shifting from one-time charcoal production as a by-product of land clearance to a dedicated coppice-management system in which either native vegetation or exotic species are periodically harvested and carbonized. The magnitude of carbon emissions reductions that may be achieved varies depending on the coppice cycle as well as the choice of tree species and carbonization technology. However, these variations are smaller than the variations that arise from the choice of baseline methodology.

The large differences in ERs associated with different baseline scenarios raise questions about how to best assess changes in GHG emissions associated with activities involving fuel substitution and land cover change. Calculating emissions reductions relative to the baseline scenario based on a single unit of land leads to systematically lower emissions reductions than calculating emissions reductions based on the amount of NRB displaced.

Recent analyses have shown that similar complications arise in the modern energy sector. When biofuels replace fossil fuels, losses in biomass and soil carbon can result in a "carbon debt" that takes decades or centuries to repay [63]. However, as this analysis shows, when the conversion

<table>
<thead>
<tr>
<th>Scenario</th>
<th>EM kiln</th>
<th>Improved kiln</th>
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<tbody>
<tr>
<td>Baseline-1</td>
<td>Baseline-2</td>
<td>Baseline-1</td>
</tr>
<tr>
<td>Baseline-IK</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>Tarch5</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Tarch10</td>
<td>0.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Tarch15</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Euc (slow)</td>
<td>1.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Euc (moderate)</td>
<td>2.8</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Fig. 9 – Net carbon emissions per hectare relative to the baseline scenario in aboveground (AG) pools, belowground (BG) pools, and soil, as well as emissions from charcoal production (Charc EM or IK) in year-30 of each scenario. Positive changes represent carbon emissions; negative changes represent carbon sequestration. Emissions are shown for charcoal production from EM kilns (dashed lines) and from improved kilns (solid lines).

Fig. 10 – Net carbon emission reductions and sequestration relative to the BAU scenario, demonstrating the impact of increasing the land area affected by BAU land clearance so that the same quantity of charcoal is produced during the 30-year project activity. Each scenario includes charcoal production from EM kilns (shaded entries) and from improved kilns (solid entries).
of natural ecosystems defines the BAU scenario, alternate post-clearance land management options may have the opposite effect: leading to fewer emissions than would have otherwise occurred. For land managers, deviations from BAU behavior must bring tangible benefits. This is not possible under Kenya’s current market conditions; land managers see much greater returns from one-time charcoal production followed by intensive grain cultivation, than they would see from any of the charcoal production scenarios explored here [20].

6.1. Charcoal and food production

The scenarios explored here shift land out of wheat production. This is not a threat to local food security as wheat is a negligible part of the local diet. However, wheat from Narok is processed for consumption in urban and peri-urban markets. Thus, shifting land that was destined for wheat production into less carbon-intensive uses may create some unmet food demand. If this were to occur on a large scale, a segment of the population could be adversely affected. Alternatively, it may induce other land clearance to meet demand, which could emit additional GHGs. These indirect effects have been estimated to have substantial impacts when biofuel production occurs at very large scales [64], but such effects are difficult to characterize in small markets.

6.2. Assessing the choice of baseline

The disparity between emission reductions arising from different choices of baseline methodology reflect the difficulty in combining emissions reductions derived from LUC and energy-based activities. One might simply ask “which baseline most accurately reflects reality?” The problem is that both can be justified with reasonable arguments. For example, land planted with E. grandis managed on a 10-year coppice cycle over 30 years would produce 10 times more charcoal than is produced from one-time clearance of native vegetation. In theory, providing that charcoal to the market would lessen demand for additional virgin land to be cleared for charcoal production. The problem with this logic is that land clearance is only partially driven by demand for charcoal. It is also driven by a desire to expand crop cultivation. Thus, the clearance of additional land also depends on the extent to which cultivation presents an attractive land use option.

This argument may make the assessment based on fixed land area seem more justifiable. However, wheat is not consumed locally. Like charcoal, wheat is simply a commodity sold to non-local markets. As was mentioned above, current policies in Kenya are not amenable to sustainable land management for charcoal production [20]. However, this may change as a result of recent legislation [2,3]. If sustainable land management for charcoal production were a viable option, then it is possible that fewer land owners would opt to plant wheat, making the assessment of emission reductions based on energy the more realistic option.

It should also be noted that the methodologies that have been developed to calculate emission reductions in existing carbon offset projects are not necessarily realistic. In some cases, realism is traded for simplicity and replicability. For example, the methodologies that have been approved for reducing or substituting the use of NRB estimate emission reductions by defining a baseline in which users switch to fossil fuels like LPG or kerosene, an unlikely scenario in most settings where NRB is common [65]. Thus, while assessment of net carbon savings based on fixed land area is certainly a more conservative assessment method, in the absence of genuine experience with land management for sustainable charcoal production, we can not determine which method better reflects reality. In any case, careful monitoring would be required to elucidate how Kenya’s charcoal market would respond to more sustainable production practices.

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Abbreviations used in the text

A/R: afforestation and reforestation
AG: aboveground
BG: belowground
BAU: business-as-usual
CDM: Clean Development Mechanism
CDM-EB: CDM Executive Board
EM: earthmound (kiln)
ER: emissions reduction
EUC: eucalyptus (modeling scenario)
GIS: Geographic Information System
GHG: greenhouse gas
GWP: global warming potential
IK: improved kiln
IPCC: Intergovernmental Panel on Climate Change
LUC: land-use change
LPG: liquid petroleum gas
NRB: non-renewable biomass
TARCH: Tarchonanthus camphoratus (modeling scenario)