The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis

Article *in* Energy for Sustainable Development · April 2013

DOI: 10.1016/j.esd.2012.07.004

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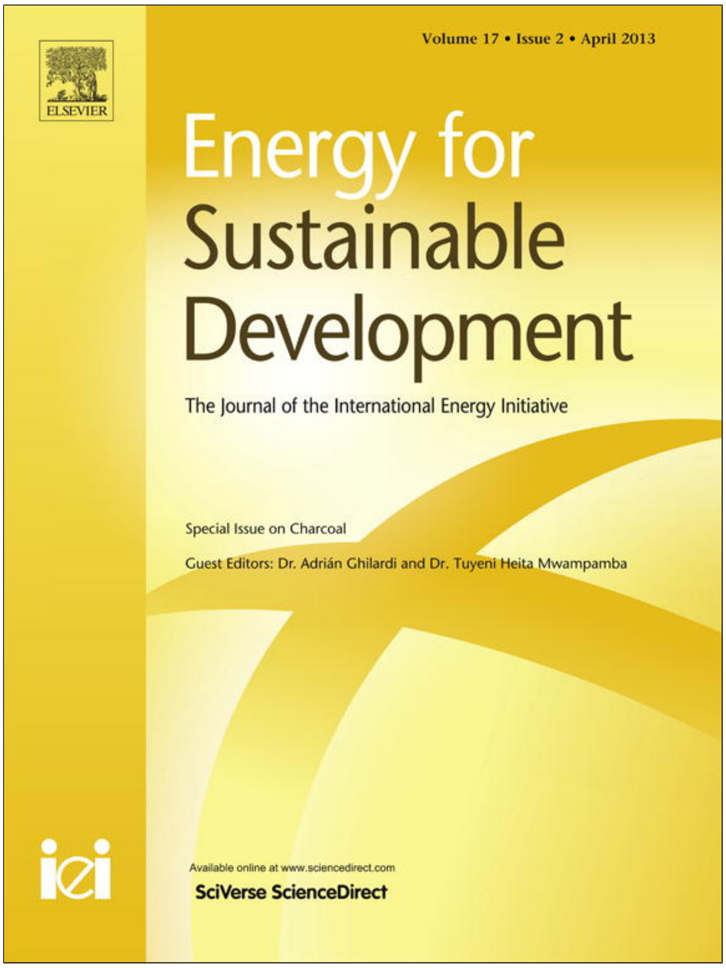
Volume 17 • Issue 2 • April 2013
ELSEVIER
Energy for Sustainable Development
The Journal of the International Energy Initiative
Special Issue on Charcoal
Guest Editors: Dr. Adrián Ghilardi and Dr. Tuyeni Heita Mwampamba
iei
Available online at www.sciencedirect.com
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Energy for Sustainable Development 17 (2013) 86–94

Contents lists available at SciVerse ScienceDirect

Energy for Sustainable Development

Review

The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis

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A R T I C L E I N F O

Article history:
Received 11 April 2012
Revised 17 July 2012
Accepted 17 July 2012
Available online 9 August 2012

Keywords:
Tropical ecosystems
Charcoal production
Deforestation
Ecosystem services
Greenhouse gases

A B S T R A C T

Charcoal production in tropical regions of the world is often perceived to have devastating ecological and environmental effects and governments, public forestry institutions and non government organizations have been particularly concerned about these charcoal-related impacts. The most commonly cited impact is deforestation, i.e., the clearance of forest or woodland. At a small spatial scale this may indeed be the case but on a larger landscape scale charcoal production most frequently results only in forest degradation. Much of the charcoal in tropical countries is commonly made in traditional earth and pit kilns with a wood-to-charcoal conversion rate of about 20% and in 2009 the contribution of charcoal production to deforestation in tropical countries with the highest rates of deforestation is estimated at less than 7%. A large proportion of the area utilized for charcoal production has the potential for rapid forest recovery especially with good post-harvest management. There are conflicting reports on the effects of deforestation on catchment hydrology with the majority of small catchment studies indicating increased runoff and low evapotranspiration while studies of large basins have shown no such changes. Emissions of greenhouse gases from charcoal production in tropical ecosystems in 2009 are estimated at 71.2 million t for carbon dioxide and 1.3 million t for methane. The failure of past charcoal policies to address environmental impacts and achieve sustainability can be attributed to erroneous assumptions and predictions by national and international organizations regarding wood-based fuels. Possible ways of enhancing charcoal policies' legitimacy and therefore effective implementation are multi-stakeholder participation and demonstration of coherence with globally recognized principles, goals and relevant international regimes, such as the Millennium Development Goals (MDGs). In this way charcoal production can significantly contribute to poverty reduction and environmental sustainability.

Contents

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0973-0826/$ – see front matter
http://dx.doi.org/10.1016/j.esd.2012.07.004

Introduction

A reassessment of the wood energy situation in developing countries, the majority of which are in tropical regions, revealed that in Asia and Africa consumption of wood energy is declining although consumption in Africa remains high while in South America, where wood energy is less important, overall consumption appears to have been rising slowly (Arnold and Persson, 2003). With high levels of poverty, the dependence on biomass energy sources continues to rise in sub-Saharan Africa (May-Tobin, 2011). This trend, coupled with inefficient wood fuel production and consumption practices, and inaccessibility by most households to other reliable and affordable commercial energy forms, is not likely to change in the near future.

Charcoal is a fuel that is produced by carbonization of biomass. Although investment in charcoal production from forest plantations is increasing in tropical regions, for the most part, biomass for charcoal production is obtained from natural forests in which natural regeneration is the main source of forest recovery. This general pattern – of almost complete dependence on natural forests for charcoal production – and the perceived unsustainable harvesting and poor post-harvest forest management, are the primary reasons why governments, non-government organizations and civil society are concerned about the environmental impacts of charcoal production (WEC, 2004). The most commonly cited impact of charcoal production is deforestation, i.e., the clearance of forest or woodland. Charcoal consumption is growing faster than firewood consumption and its use is becoming a much larger part of the wood energy's total in Africa and South America. However, in tropical America the use of charcoal varies from region to region. For example, in Brazil charcoal is mainly used in manufacturing while in Central America it is mostly used in the food industry and to some extent as a domestic energy source. In sub-Saharan Africa charcoal is predominantly a household cooking energy, especially for urban dwellers.

Understanding the charcoal situation has always been hampered by lack of reliable information, partly because only a very small fraction of charcoal production is recorded and assessment of the actual magnitude of use, and the impacts on forests and rural livelihoods, has consequently been difficult to determine although this has been the subject of considerable debate (Arnold and Persson, 2003; FAO, 2010a). Apparently where high consumption levels are coupled with poor forest management and regulation of the charcoal trade, the impact of charcoal tends to be underestimated (Mwampamba, 2007). The objective of this paper is to review traditional charcoal production methods and assess their ecological and environmental impacts across tropical ecosystems of the world. The paper is based on literature review and meta-data analysis and seeks to provide a broader perspective of the concerns surrounding charcoal production in tropical regions of the world and its potential to contribute to the attainment of the Millennium Development Goals (MDGs), especially those that aim at poverty reduction and environmental sustainability.

Tropical forest ecosystems of the world are diverse and range from closed moist (rain) forests to open woodlands and scrub and contain millions of species of plants and animals. These ecosystems lie between the Tropic of Cancer in the north and the Tropic of Capricorn in the south. They are found in at least 114 countries (Table 1) and cover nearly 734 million ha in Africa, 821 million ha in South and Central America and 360 million ha in Asia and Oceania (Unesco, 1978). Detailed description of tropical biomes can be found in Holzman (2008) but the main characteristics of tropical ecosystems are summarized in Table 2.

Table 1
Extent of land and forest area in tropical regions of the world[a].

Region	Number of countries	Land area (million ha)	Forest area (million ha) in 2000
Africa	47	2251.0	634.2
Asia	15	824.9	278.8
Central America	25	262.4	77.4
Oceania	17	54.0	35.1
South America	10	1387.0	834.1

[a] Based on FAO (2005).

Charcoal production techniques

The impacts of charcoal on ecosystems occur at every stage in the production–consumption chain but here we focus only on the impacts of production in tropical forest ecosystems. Almost all the charcoal in tropical countries are produced from aboveground tree biomass, implying that whole or parts of trees must be felled and wood carbonization is commonly made in traditional kilns of which there are many types (Foley, 1986). For example, the bulk of the charcoal in tropical Africa is made in earth kilns of which there are two types: the pit kiln and the surface earth-mound kiln. The pit kiln is constructed by digging a pit or trench in the ground and filling it with wood before covering the wood pile with green leaves or metal sheets and soil to prevent complete burning of the wood to ash during carbonization. The earth-mound kiln is built by covering a pile of wood on the ground with leafy or herbaceous material and soil. Modified forms of the surface earth kiln may have ventilation channels, such as chimneys (e.g., the Casamance kiln). Other kilns are made of bricks (brick kilns) or metal (metal kilns) and although these types have the advantage of being moved from place to place, they are not in common use. The earth mound kiln is preferred over the pit kiln where the soil is rocky, hard or shallow, or the water table is close to the surface. The pit kiln is more commonly used in Asia and America. The wood-to-charcoal conversion rate on a dry weight basis varies with each kiln type (Table 3), but also with the experience of the charcoal producer and weather conditions. Analysis of data for 209 charcoal kilns studied in Africa, South America and Asia, including modified earth kilns (Ando et al., n.d.; Kimaryo and Ngereza, 1989), brick kilns (Pennise et al., 2001; Smith et al., 1999; Swami et al., 2009) and drum kilns (Smith et al., 1999) and those given in Table 3, gave a mean wood-to-charcoal conversion rate of 0.204 ± 0.007. However, the conversion rate for the most commonly used kilns (Table 3) of 0.188 ± 0.008 is significantly different from that of 0.281 ± 0.011 for the other kiln types ($t = 4.98$, $p < 0.0001$).

Impacts of charcoal production on tropical forest ecosystems

Deforestation and forest degradation

In almost all countries where charcoal is produced there have been reports highlighting concern about deforestation and forest degradation that accompanies the production process (Hofstad et al., 2009). Forest degradation refers to less obvious changes in the woody canopy cover while deforestation is the more or less complete loss of forest cover that is often associated with forest clearance (Grainger, 1999). Degradation therefore represents the temporary or permanent reduction in the density, structure, species composition or productivity of vegetation cover.

The degree of forest clearing for charcoal production varies considerably among countries and even sites within each country. Trees used for charcoal production are cut with axes, machetes or chainsaws, often by stumping that leaves behind the basal portion (<1.5 m aboveground) of the trunk while the cut trunk and main branches are cut into appropriate billets or logs that are piled to form a kiln for carbonization into charcoal. Minor canopy branches and twigs (brushwood) are abandoned in situ or gathered to form brushwood piles in the area surrounding the kiln. Tree cutting for charcoal production varies along a continuum from selective cutting to clear cutting which makes it difficult to distinguish the impact of charcoal production between deforestation and forest degradation.

Table 2
Main characteristics of tropical ecosystems[a].

Tropical ecosystem	Climate type	Mean annual temperature (°C)	Precipitation (mm per year)	Ratio of potential evapotranspiration to precipitation	Growing period (months)
Equatorial	Tropical perhumid	28	2000	<1	11–12
Subequatorial	Tropical humid	25	1300–3000	<1	7–10
Subtropical	Tropical mesic	21–32	500–1500	>1	4–6
Outer tropical	Tropical semi-arid	20–33	350–1000	>2	2–3

[a] Based on Montagnini and Jordan (2005).

Generally the impact of producing a specified amount of charcoal depends primarily on tree size and density which vary among the different tropical forest ecosystems (FAO, 2005), species composition, site history, land tenure and the policy and legislative mechanism. Whether tree harvesting for charcoal production causes deforestation remains debatable and obviously depends on the spatial resolution of the analysis.

In West Africa selective cutting is normally used to harvest wood for charcoal production such that only key charcoal tree species are harvested resulting in a degraded forest with reduced cover as opposed to clear cutting that results in deforestation (Tappan et al., 2004; Touré et al., 2003; Woomer et al., 2004; Wurster, 2010). Work done in a Sudanian savanna woodland in Burkina Faso (Sawadogo et al., 2002) and Togo (Kouami et al., 2009) also found that 50% to 76% of the biomass is removed in selective cutting of firewood and charcoal species. This would imply that forest cover may remain above 10% after selective cutting for charcoal production. Indeed, Ribot (1993) argued that deforestation in the West African tropical forests caused by charcoal production has not been demonstrated, suggesting that forest degradation following harvesting for charcoal production is probably more prevalent than deforestation. Obviously selective cutting can cause depletion of preferred species with adverse affect on the composition and biological productivity of the forest resource (Arnold and Persson, 2003).

In east and southern Africa clear-cutting during charcoal production, at least at small spatial scales, appears to be more prevalent than selective cutting. For example, in Mozambique, charcoal production in a dry forest is characterized by a "clear-felling system" since almost all species are used (Herd, 2007; Pereira et al., 2001). In Zambia regulated charcoal production in forest reserves was based on the shelterbelt and strip clear-cutting system (Fig. 1). Chidumayo (1990) observed that 97% of the standing wood biomass was harvested for charcoal production in central Zambia which would be equivalent to clear-cutting around the kiln site. In the Morogoro region of Tanzania, there is little species and size selection in tree felling for charcoal, such that there is virtual clear-felling of the woodland around a kiln site but harvesting intensity tends to decline with increasing distance from settlements and transportation routes (Luoga et al., 2002). Observations made in the Brazilian Amazon also indicate that there is no selection of species cut for charcoal production (Swami et al., 2009).

One could argue that at a small spatial scale the absence of species selection for charcoal production in many charcoal production systems, perhaps with the exception of a few tropical countries, such as Mexico, largely leads to temporary deforestation which can be distinguished from permanent deforestation which occurs when cleared land is converted to other non-forest land uses, such as permanent agriculture. On a larger landscape scale, at least in tropical Africa, charcoal production most frequently results in forest degradation as has been documented by Ahrends et al. (2010) around Dar es Salaam in Tanzania and perhaps other African cities (Khalifa, 1982; Pereira et al., 2001; Ribot, 1993). Similar processes of forest degradation have been reported for areas supplying charcoal to Georgetown in Guyana (Clarke, n.d.). Luoga et al. (2002) reported that the removal of 4.64 t/ha for charcoal production in public lands in the Morogoro region of Tanzania exceeded the mean annual increment of 3.15 t/ha and therefore concluded that harvesting was causing forest degradation through changes in the structure and composition of the vegetation. Arnold and Persson (2003) also report that charcoal production can materially alter the structure and productivity of the harvested areas and concluded that charcoal production in eastern and southern Africa can lead to transformation of woodland to bush, and bush to scrub, over very large areas. But under severe wood resource depletion, even stumps left over from previous charcoal production may be dug up and used to make charcoal (Oduori et al., 2006) which results in severe reduction in the potential for natural forest regeneration and in some cases permanent deforestation even in the absence of land use change.

In assessing the impact of charcoal production in tropical ecosystems, we have assumed that clear-cutting for charcoal production is the primary reason for forest clearing although these assumptions

Table 3
Average wood-to-charcoal conversion rates of three types of commonly used kilns in tropical regions of the world.

Kiln type	Sample kilns	Wood-to-charcoal conversion rate (charcoal mass/dry wood mass) ± 1se	Source of data
Surface earth mound	77	0.257 ± 0.010	Chidumayo (unpublished); Kimaryo and Ngereza (1989); Pennise et al. (2001); Smith et al. (1999); Swami et al. (2009)
Casamance surface earth mound	38	0.168 ± 0.012	ESMAP (1991); Kimaryo and Ngereza (1989)
Pit mound	62	0.118 ± 0.012	Ando et al. (n.d.); ESMAP (1991); Kimaryo and Ngereza (1989)

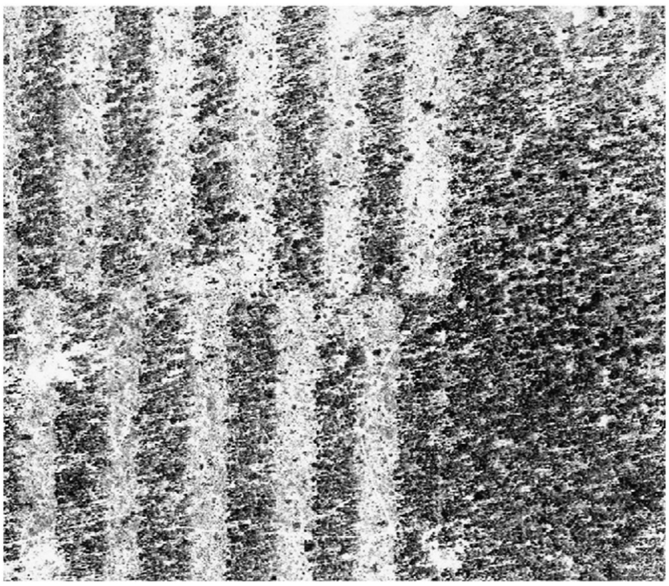

Fig. 1. Aerial view of the shelterbelt and strip clear-cutting system for regulated charcoal production in the former Soli Forest Reserve, central Zambia.

may not be valid for all the tropical regions of the world. We have used the annual rates of deforestation during 1990 to 2005 and wood biomass stocking rates given by FAO (2005) and wood-charcoal production data available at www.faostat.fao.org/faost for 2009 to estimate total deforestation in 2009 for each tropical country using the following equation:

$$\text{Deforestation}_{2009}(\text{ha}) = \left(\text{charcoal}_{\text{produced}}(1/0.19)\right)/\text{biomass}_{\text{density}}$$

where 0.19 is the wood-to-charcoal conversion rate for earth kilns (see above) and $\text{biomass}_{\text{density}}$ is the country wood biomass stocking rate (FAO, 2005). Of course, where charcoal production follows selective logging for timber, our deforestation values will be underestimates because post-logging stocking rates would be lower but deforestation values would be overestimates if charcoal production is a by-product of forest conversion to other land uses, such as agriculture. For example, 20.3% of tropical moist forests are reported to have been selectively logged (Asner et al., 2009). Where charcoal is being sourced from forests, studies have shown that it is usually from land being cleared for farming which support the view that charcoal production is seldom the primary source of depletion or removal of forest cover on a large scale (Arnold and Persson, 2003). In central Zambia, nearly 70% of forestland that was cleared for charcoal production was subsequently converted to agriculture and settlement (Chidumayo et al., 2001) although other researchers have noted that charcoal production may also follow forest clearing for agriculture (Hofstad et al., 2009). Furthermore with population increase between 2005 and 2009 our deforestation estimates are likely to be underestimates and therefore should be considered as tentative and only indicative of a broad overview of the probable magnitude of deforestation caused by charcoal production in tropical regions of the world.

Estimated annual deforestation rates caused by charcoal production in 2009 ranged from 5.40 km^2 in Oceania to 390 km^2 in Central America, 2400 km^2 ha in South America, 5100 km^2 in Asia and 29,760 km^2 in Africa. Africa accounts for nearly 80% of the charcoal-based deforestation in the tropical regions of the world. Among the 17 countries with the highest rates of deforestation in the world, the proportion of total deforestation attributed to charcoal production ranged from 0.33% in Zimbabwe to 33.16% in Tanzania, but in terms of actual forest cover loss the highest rates of loss occurred, in ascending order, in Zambia, DR Congo, Nigeria, Brazil and Tanzania (Fig. 2). A major distinction

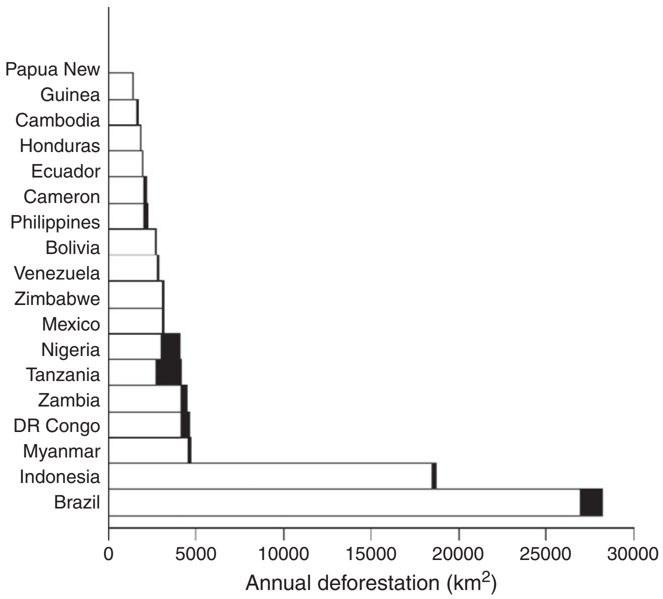

Fig. 2. Deforestation caused by charcoal production (black bars) and deforestation caused by other factors (plain bars) in 17 countries with the highest rates of deforestation in the world.

among these countries is that the charcoal in African countries is largely used for cooking by urban households whereas in Brazil charcoal is used for industrial purposes. Nevertheless, for the countries with the highest rates of deforestation, the sub-regional average proportion of total deforestation caused by charcoal production ranged from $2.5 \pm 1.80\%$ in Central America to $2.84 \pm 0.67\%$ in South America, $3.90 \pm 1.88\%$ in Asia and $14.07 \pm 5.27\%$ in Africa; the overall mean was $6.9 \pm 2.3\%$. It is apparent therefore that charcoal production contributes less than 7% to total deforestation in most tropical countries. In fact, Modan (unpublished) estimated that wood fuel harvesting for urban markets affected less than 2% of the total wooded area in African countries. However, although deforestation caused by charcoal appears to be small at national and regional scales, there is no doubt that it can be a serious environmental problem at a local scale.

Post-harvest forest regeneration

Regeneration of tropical forest trees occurs through either sexual or vegetative means. Sexual regeneration is achieved through seed germination and establishment of seedlings and their recruitment into the tree phase. Vegetative regeneration occurs through the recruitment of sprouts or resprouts into the tree phase from pre-existing trees that are cut or damaged, sometimes termed coppice. Sprouting is the production of secondary trunks as an induced response to injury or to profound changes in growing conditions. The importance of each of these regeneration mechanisms depends on the floristic composition of the forest and the type of disturbance. Seedlings are probably a significant source of regeneration in tropical moist forests after disturbance, such as cutting, than in tropical dry forests where regeneration from saplings is more important. However, resprouting is a common source of regeneration in both moist and dry forests because many tree and shrub species are capable of resprouting (Paciorek et al., 2000) following injury. In recently cut and cleared dry forests of Central America, stem coppicing and root sprouting rapidly restore the number of species on a given site (Ewel, 1977; Murphy and Lugo, 1986; Vieira et al., 2006). Sprouting from cut stumps is a common regeneration mode after forest cutting in Venezuela (Uhl et al., 1981). However, resprouting may be more important in tropical dry forests than in moist forests because of the longevity of trunk bases and the adaptation of plants to seasonal drought.

Many tropical forest species have the potential to regenerate after clearing for charcoal. Observations made in eastern Senegal indicate that dry forest areas were cut for charcoal in 1940, 1969 and again in the mid-1980s (Ribot, 1993) and charcoal makers are reported to return to harvest the same area after 9 to 12 years in Mali, Niger and Burkina Faso (Nygård et al., 2004). Interestingly, similar observations have been made for temperate forests in Mexico where forest recovery periods are estimated at 10 to 15 years (Aguilar et al., 2012). In Zambia, return periods to previous clear-cut areas for charcoal production range from 20 to 30 years (Chidumayo et al., 2001). In Kenya a 14-year rotational harvesting period has been proposed for regrowth of acacia dry forest (Okello et al., 2001). Woodlands in Tanzania appear to recover relatively well following harvesting for charcoal production (Hosier, 1993) but recovery periods of degraded woodland after charcoal production range from 8 to 23 years (Malimbwi et al., 2001, 2005). Clear cutting removes the entire canopy and for tropical forests that regenerate vegetatively from stump sprouts and resprout saplings, this is the best way of promoting regeneration (Chidumayo, 1997, 2004). Such forest regrowth usually has higher tree species diversity than the old-growth forest that it replaces and the danger of species loss is minimized (Chidumayo, 1997), although such clear cut areas may sometimes experience severe visible crusting and soil erosion (Hosier, 1993). On the other hand, selective cutting gives a competitive advantage to uncut residual trees that may suppress regrowth of cut trees and saplings thereby leading to more permanent forest degradation.

Apparently, the forest regeneration rates are a function of forest type, cutting system, rainfall, fire management and grazing intensity

Fig. 3. Wood biomass accumulation in regrowth miombo woodland under different management levels in Zambia: 1 (●) for pre-1980s characterized by good forest management ($y = 103.5 - 129.7 * 0.94x$), 2 (○) for the 1980s characterized by declining forest management ($y = 27.5 * \ln(x) - 37.0$) and 3 (◊) for the 1990s characterized by lack of forest management ($y = 15.7 * \ln(x) - 27.0$).
Based on data in Chidumayo (1988, 1990, 1991, 2002, unpublished).

(Hosier, 1993; Ribot, 1993) and often the recovery period is prolonged through heavy grazing and uncontrolled burning. A study in northwestern Costa Rica observed that areas where cattle grazing was excluded were structurally more similar to a mature dry forest than those that were grazed on (Stern et al., 2002). Unfortunately, tropical forest regrowth remains virtually unmapped which has made it difficult to quantify the extent of secondary forest although some isolated attempts are being made to generate such data. For example, a recent national forest inventory in Zambia estimated that 65% of the forests in Zambia are re-growth from previous use and acknowledges the great potential that exists for natural regeneration (Zambia Forestry Department and Food and Agriculture Organization of the United Nations, 2009). Asner et al. (2009) reported a conservative estimate of 1.2% of tropical moist forest to be undergoing decadal-long secondary growth worldwide but ranging from 0.8% in Asia and Oceania to 1.8% in South America and 2.4% in Central America; no estimate was made for Africa due to lack of appropriate data. Lanly and Clement (1982) estimated that 20% of open woodland in Africa is made up of regrowth on fallows after abandonment.

The speed and path of forest recovery after forest clearing are linked to post-harvest land use intensity. A study in Puerto Rico found that sites previously used for charcoal production as evidenced by the presence of charcoal pits required shorter periods to recovery than those where land was used for settlement and agriculture (Colón, 2006). Also post-harvest management of charcoal production areas plays a crucial role in facilitating forest recovery, both in terms of species and biomass accumulation. For example, the decline in post-harvest forest management in miombo woodlands in Zambia has contributed to a significant reduction in wood biomass accumulation rendering the current charcoal production system unsustainable (Fig. 3).

The rate of forest regeneration on kiln sites following charcoal production is different from that of surrounding areas. The intense impact at kiln site caused by soil digging and extreme heat (500–700 °C) during carbonization (Boutette and Karch, 1984) delays forest recovery for many decades and during this period the secondary vegetation on kiln sites is dominated by herbaceous plants, especially grasses. Recurrent dry season fires, especially in dry forests, further retard the development of the woody vegetation on kiln sites. For example, Chidumayo (1988) found dense tall grass with little woody plant regeneration on kiln sites 13 years after charcoal production in a wet miombo woodland in Zambia. In Central America charcoal pits persist for many decades (Colón, 2006) suggesting that forest recovery in pit kilns is impaired for a long time after charcoal production. Because of this very slow forest regeneration, deforestation on kiln sites can be regarded as permanent. Unfortunately, published studies that have recorded the area covered by charcoal kilns are very rare. The area covered by earth kilns in relation to total harvested area in Zambia was estimated at about 5% (Chidumayo, unpublished). This is the area that can be considered to be permanently deforested due to charcoal production. Thus a large proportion of the area utilized for charcoal production is only affected by temporary deforestation or forest degradation that has good potential for rapid forest recovery unless the area is not well managed or is converted to other land uses.

Impacts on soil

For earth-based kilns, charcoal production impacts the soil at two different levels of intensity. Intense impact occurs at the kiln site as a result of the extreme heat generated during the carbonization process and the digging to make a pit and/or soil to cover the wood pile. Low impact occurs in the area surrounding the kiln where the wood is harvested. Soil impacts in the harvested area are probably similar to those of any low impact forest clearing that does not result in land use change.

Few studies have assessed charcoal production impacts on soil at the kiln site. Oguntunde et al. (2008) observed that soils under charcoal kilns in Ghana had reduced bulk density and surface albedo, higher porosity and soil-surface temperature and higher infiltration rates than the adjacent field soil. The study also found that the saturated hydraulic conductivity of soils under charcoal kilns increased significantly ($p < 0.01$) from 6.1 ± 2.0 cm h^{-1} to 11.4 ± 5.0 cm h^{-1}, resulting in a relative increase of 88%. Apparently, the higher infiltration rates on kiln soils reduced runoff by up to 37% (Ajayi et al., 2009). However, a study in Jamaica showed that although carbonization had significant impacts on soil pH, water-holding capacity, texture and nutrient content, it reduced percolation rates and water retention, as well as soil aggregates, which increases the risk of soil erosion (McLaughlin, 2008). The majority of the studies agree that kiln soils have a higher nutrient status than the surrounding soil. Chidumayo (1994) found that wood carbonization increased soil pH and exchangeable phosphorus and potassium in a miombo woodland Alfisol/Ultisol in Zambia. A review by Glaser et al. (2002) on the ameliorating effects of charcoal on highly weathered soils in the tropics confirms that carbonization results in higher nutrient retention and availability on the kiln sites, perhaps because of the heat and presence of charcoal fines in the kiln soil.

It is apparent that the soil in the harvested area surrounding kiln sites is rarely significantly affected by tree-clearing. Chidumayo and Kwibisa (2003) assessed the effects of clearing a miombo woodland on soil nutrient status at four sites over a 10-year period in central Zambia and found that although clearing affected topsoil (0–30 cm depth) organic matter and available phosphorus, these effects were not statistically significant compared to forest clearing followed by cultivation that significantly reduced soil organic matter. However, these authors observed that site and year had the most significant effects on soil nutrient stocks, regardless of whether the woodland was cleared or not and that fire reduced topsoil organic matter and nitrogen at most of their study sites. However, Sioli (1984) noted that deforestation in Amazonia results in soil compaction, which then contributes to enhanced surface runoff due to the corresponding reduction in infiltration rates.

Greenhouse gases emissions during carbonization

Charcoal from most earth-based kilns is produced in an oxygen-poor environment that results in the formation of products of incomplete combustion, such as methane. Charcoal production therefore affects global warming through the production and emission of greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4). Although carbon monoxide is one of the products of incomplete combustion during charcoal making, it is not listed as a greenhouse gas by the IPCC as it is considered to be short-lived in the atmosphere (IPCC, 2007). Kammen and Lew (2005) have shown that emissions during charcoal production

Table 4
Greenhouse gas emissions from charcoal production in tropical ecosystems of the world.

Region	Estimated charcoal production (2009) in million tonnes	Greenhouse gas emissions (million tonnes)			
		Carbon dioxide	Methane	Methane (CO_2 equivalent)	Total CO_2
Africa	26.116	46.70	0.84	20.93	67.63
Asia	5.006	8.95	0.16	4.01	12.96
Central America	1.061	1.90	0.03	0.85	2.75
Oceania	0.012	0.02	0.00	0.01	0.03
South America	7.621	13.62	0.24	6.10	19.72
All regions	39.816	71.19	1.27	31.85	103.04

have a greater global warming contribution than emissions from charcoal burning. The emission factors for charcoal production have been calculated in a number of studies (Adam, 2009; Akagi et al., 2010; Pennise et al., 2001; Smith et al., 1999; Ward et al., 1999). Observations made on 11 kilns in these studies gave emission factors (g greenhouse gas/kg charcoal produced) of 1788 ± 337 for CO_2 and 32 ± 5 for CH_4. To calculate emission quantities from charcoal production in tropical ecosystems, we used FAO estimates of wood-charcoal production in 2009 available at www.faostat.fao.org/faost and the results are presented in Table 4. The values given in Table 4 represent upper limits of emissions because some of the CO_2 emitted is sequestered by the regenerating forest after charcoal production. Africa is by far the largest emitter of greenhouse gases from charcoal production, accounting for nearly two-thirds of the emissions, followed by South America that contributed nearly 20% of the emissions from tropical regions of the world.

Effects on catchment hydrology

Hydrologists define a watershed as a land area that captures rainfall and conveys the surface runoff to an outlet in the main flow channel (Becerra, 1995). In this sense a watershed is similar to a catchment. Within a watershed, the processes of deforestation, soil loss and water quality deterioration are closely interrelated. Often an increase in runoff from watersheds is the immediate effect of forest clearing. A number of catchment studies have been carried out in tropical regions of the world to assess the influence of forest cover on runoff. However, differences in the results of catchment studies may be due to variations in the size of the studied catchments. Lørup and Hansen (1997) found that specific flow is relatively independent of catchment size when the catchment area is more than 100 ha. It is also difficult to isolate the impacts of forest clearing for charcoal production from other causes of deforestation in a catchment area. Therefore only tentative conclusions can be made from studies of catchments experiencing multiple causes of deforestation and other forms of land cover change.

For smaller catchments, changes in land cover due to deforestation cause an increase in the annual mean river discharge, less water uptake and less evapotranspiration but these responses are quickly reversed due to secondary forest regrowth (D'Almeida et al., 2007). Reductions in leaf canopy and root zone depth following deforestation have also been observed to diminish evapotranspiration and increase runoff (Nepstad et al., 1994; Tobón et al., 2000). These observations are in reasonable agreement with general expectations of enhanced water yield over cleared sites (Bosch and Hewlett, 1982; Oyebande, 1988; Sahin and Hall, 1996; Tucci and Clarke, 1997), a pattern that follows directly from the observed reduction in evapotranspiration — arising predominantly from declines in transpiration, interception and water uptake. Studies of small catchments (1–2 km^2) on the upper Kafue Basin in a miombo woodland in Zambia have also shown that woodland clearing, especially when accompanied by cultivation and grazing, increased annual stream flow and peak stream flow and reduced flow duration (Mumeka, 1986; Sharma, 1985).

Observations based on small catchments have not always been supported by studies on larger river basins (> 100 km^2) in the Amazon Basin (Bruijnzeel, 1990; D'Almeida et al., 2007). In fact this led D'Almeida et al. (2007) to note that one cannot be entirely sure whether deforestation is affecting the water cycle in Amazonia, since the inherent effects could be occurring at a small scale but not a large scale. However, a study covering a 50-year period of discharge of Tocantins River catchment (175,360 km^2) in southeastern Amazonia, central Brazil, revealed that while precipitation over the basin did not change significantly between the period with little land cover change (1949–1968) and the period of intense land cover change (1979–1998), the annual mean discharge of the river during the latter period was 24% greater than for the period of little land cover change while the high-flow season discharge increased by 28% which were attributed to vegetation cover change (Costa et al., 2003). It has also been argued that increasing trends in discharge observed in time series data of the Amazon Basin between the late 1950s and the early 1980s that were associated with deforestation in upstream areas (Gentry and Lopez-Parodi, 1980; Rocha et al., 1989), eventually tended to retreat to their long-time averages (Marengo, 1995), suggesting the temporary nature of these hydrological responses to forest clearing.

Secondary (regenerating) forests account for about 30% of the accumulated deforested area in Amazonia (Skole and Tucker, 1993), and measurements taken over a 2.5-year-old secondary forest in the eastern part of the Amazon Basin showed intermediate values of evaporation compared to typical estimates for pastures and primary forests (Hölscher et al., 1997) while the values for a 3.5 year old regrowth had similar evapotranspiration values as a primary forest (Sommer et al., 2002). Therefore, the shifting patterns of clearing and regrowth are likely to complicate efforts at examining land-use induced hydrology changes in tropical ecosystems (D'Almeida et al., 2007). Reduction in runoff on larger river basins is also due to the regulatory function of wetlands and man-made reservoirs in the head and middle waters of rivers (Beilfuss and dos Santos, 2001).

Impacts on ecosystem services

Tropical forests, like other forest ecosystems, provide both goods and services that benefit mankind. The tangible goods provided by tropical forests include timber, wood fuel (firewood and charcoal) and non-wood products, such as bush meat, honey, bees wax, edible insects, fruits, tubers and medicines that contribute to human well being (FAO, 2010b). The other services are regulation of water flow, carbon sequestration, protection of land from soil erosion and provision of habitats for wildlife species (IGBP, 1995; Sunderlin et al., 2005). Through the regulation of water flow, forests contribute to the maintenance of wetland ecosystems, such as swamps and floodplains, and fish resources that wetlands harbor. Although the impacts on human well being of some ecosystem services provided by forests are indirect, they are nonetheless important for sustaining livelihoods and environmental health and security in the basin. Forests regulate stream flows by intercepting rainfall, and absorbing the water into the underlying soil, and gradually releasing it into the streams and rivers of its watershed (Bruijnzeel, 1990). This minimizes both downstream flooding and drought conditions. Water circulation is closely linked to the climate regulation function of ecosystems, such as tropical forests. Fresh water is intimately involved in the provision of food, wood and non-wood products through photosynthesis, maintenance of soil fertility, and flood and erosion control. Forests also influence the local and global climate; they absorb atmospheric carbon and replenish the oxygen in the air we breathe (IPCC, 2011). Deforestation and forest degradation caused by charcoal production, affect both local livelihoods and national economies (MA, 2005), and much of this is occurring in tropical forests (CBD, 2010).

As already noted, charcoal production contributes to deforestation through the growing demand for wood biomass energy (Defries et al., 2010) as well as through fragmentation of habitats and forest degradation at the local level (Nellemann and Corcoran, 2010). Over the years, charcoal production has contributed to the loss of resilience in tropical forest ecosystems (Thompson et al., 2009). Further, the value of total forest removals is increasingly being questioned while values of the contribution of employment and services have been further marginalized (FAO, 2010b). Also affected are market based mechanisms for the promotion of the forest sector e.g., eco-tourism, sale of certified forest products, payments for environment services (Crowe and ten Kate, 2010). Charcoal making has been viewed as a leakage under REDD+ mechanisms thereby affecting any co-benefits that may be realized from such schemes (UNFCCC, 2010). Thus, benefiting from REDD+ payments for those tropical countries engaged in charcoal production will mean that some forms of sustainable charcoal production as well as stringent MRV systems are put in place that effectively account for the leakages thereof.

Policy and management challenges

Concerns over the role of wood fuel extraction in tropical deforestation and the wood fuel shortages peaked in the late-1970s and the 1980s and these formed the basis for policy and program interventions in many developing countries in the subsequent decades (World Bank/ESMAP, 2001). These interventions were designed to either reduce wood fuel demand, increase supplies, or some combination of the two. Supply-side approaches aimed to establish wood fuel plantations, especially in peri-urban areas, or to encourage increased planting and management of trees by farmers in wood fuel deficit areas. In addition, government regulation of the charcoal industry increased in many regions by imposing taxes and restrictions on transport and exports. Except in a few cases, these policy and program interventions failed to effectively deal with the problem of charcoal-based deforestation and its associated environmental concerns. Although there is a growing awareness that wood fuels may not always be the primary cause of deforestation (Arnold and Persson, 2003; May-Tobin, 2011), broad claims of a significant link between wood fuel use and deforestation, as well as forecasts of widespread wood fuel shortages have continued. For example, a 1995 forestry policy paper by the Asian Development Bank (ADB) claimed that 'there is increasing evidence that the biggest threat to tropical forests of Asia is uncontrolled fuel wood collection and unsustainable agriculture', and projected an annual fuel wood deficit for the region of 500 million m^3 by the year 2000 (ADB, 1995).

Charcoal policies reflect government objectives and development priorities and their effective and efficient implementation depends not only on whether they are factually appropriate, but also on their legitimacy (Sepp, 2008). Two ways of enhancing legitimacy are multi-stakeholder participation and demonstration of coherence with globally recognized principles, goals and relevant international regimes, such as the Millennium Development Goals (MDGs). Often however, governments ignore charcoal as a main source of energy and leave it to the informal sector while attempting to discourage its use and mitigating its prevalence and disregarding the role that charcoal can play in rural development especially that production utilizes a locally available and potentially renewable resource. The charcoal industry can generate employment and local income in both rural and urban areas. Sepp (2008) gives the example of Sudan where:

- Charcoal is recognized as a key source of energy.
- There is a specific institution to implement wood energy policies.
- Production of charcoal from plantations and natural woodlands is well planned.
- Resources are allocated on a yearly basis for plantation establishment.
- There is strong public and private sector participation.
- Charcoal is a formal and lucrative industry.
- There are clear marketing arrangements and rules.
- Traders are organized into a formal association recognized by the government.
- The government raises royalties and taxes, which are reinvested in establishing plantations.

The failure of past charcoal policies can therefore be partly ascribed to erroneous assumptions and predictions by national and international organizations regarding wood-based fuels. Wood fuel problems are now increasingly regarded as being rooted in more systemic, albeit locally site-specific, land tenure, fiscal and incentive policies, urban energy markets, and misallocation of forests and cropland that all affect the charcoal production chain (Mwampamba, 2007; Sepp, 2008; Zulu, 2010). Therefore, precise data on the charcoal value chain provide an excellent entry point for shaping sound charcoal policy and management frameworks. In many countries, the forest sector's contribution to the national economy is marginal (<4%), due to the fact that production and use of wood-based fuels are informal and thus escape official statistics. Consequently, forest governance receives little attention and insufficient budgetary allocations. For this reason, national funding often fails to adequately reflect the revenue needs of local governments. In consequence, local branches of the forest service display low human, technical, and enforcement capacities. This problem is often exacerbated by half-hearted or arbitrary decentralization of forest governance which leaves local administrators ill prepared for the challenge of promoting community involvement or investment by the private sector. Such institutional weaknesses lower the morale of local staff, and invite corruption. Corruption coupled with unclear policy, and legal frameworks is seen as a major cause of unregulated or even illegal charcoal businesses in many parts of the tropical world.

There is also need for a significant shift from open-access forests towards secure tenure and sustainable forest management. Open access to natural resources carries the risk of unsustainable overexploitation as typified by the so called "tragedy of the commons". By contrast, sustainable forest management presupposes clear and secure long-term forest tenure through the awarding of appropriate property rights. By example, a community may be granted exclusive control over natural woodlands growing on their territory, and the exclusive right to sell wood-based fuels harvested/produced thereon (Agrawal et al., 2008). In return, the community would be bound to enter into a formal agreement with the forest service to manage the woodland sustainably either through the use of improved kiln technologies and/or prescribed management of designated production areas to ensure forest health and rapid post-harvest natural regeneration and provisions for barring outsiders from obtaining local cutting permits.

Conclusions

Currently charcoal production in tropical countries of the world largely depends on natural forests in which natural regeneration is the main source of forest recovery. This general pattern – of almost complete dependence on natural forests for charcoal production – and the perceived unsustainable harvesting and poor post-harvest forest management, are the primary reasons why there is widespread concern about the environmental impacts of charcoal production. Nevertheless, broad claims of a significant link between wood fuel use and deforestation, as well as forecasts of widespread wood fuel shortages advocated in the past are not supported by current knowledge about charcoal production in tropical countries.

The spatial scale of analysis is key to determining whether charcoal production causes deforestation or not. At production site level tree cutting tends to be non-selective and production often leads to temporary deforestation while at landscape level production leads to forest degradation characterized by a mosaic of patches exhibiting variable levels of disturbance. Assuming clear-felling of trees, charcoal production contributes <7% to total forest cover loss in tropical countries. Clearly other causes of deforestation are more important than charcoal production. Fortunately, tropical forests have a high potential for natural regeneration and investment in good post-harvest forest management should ensure sustainable charcoal production and improving kiln carbonization efficiency will further enhance this sustainability.

But making charcoal production sustainable is still faced with policy challenges that must be effectively addressed. Wood fuel problems are now increasingly regarded as being rooted in more systemic, although site-specific, land tenure, fiscal and incentive policies, urban energy markets, and misallocation of forests and cropland that all affect the charcoal production chain. A significant shift from open-access forests towards secure tenure is key to sustainable forest management because sustainable forest management presupposes clear and secure long-term forest tenure through the awarding of appropriate property rights to land owners, including communities. In all this, enhancing policy and program legitimacy through multi-stakeholder participation and demonstration of coherence with globally recognized principles, goals and relevant international regimes, such as the Millennium Development Goals (MDGs), will play a pivotal role in ensuring environmental and socio-economic sustainability of charcoal production in tropical forest ecosystems.

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