Health and Greenhouse Gas Impacts of Biomass and Fossil Fuel Energy Futures in Africa

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Bioenergy plays a major role in the energy mix in Africa today, but both the human health and environmental impacts associated with reliance on this fuel structure are significant. This article looks at a number of scenarios for the widespread use of sustainable forest management practices, charcoal production, the use of improved stoves, as well as to more rapid introductions of fossil-fuel energy systems. These scenarios are analysed for various environmental and health impacts, and it was found that sustainable bioenergy practices could, in theory, save millions of lives through improved carbon management and infrastructure. Results also showed the potential for biofuels to contribute to transportation needs and help facilitate a low carbon infrastructure system.

Bioenergy resources (wood, charcoal, dung, and agricultural residues) are vital to basic welfare and economic activity in developing nations. In sub-Saharan Africa (SSA), biomass provides more than 90% of household energy needs in many nations. The combustion of biomass emits pollutants that currently cause over 1.6 million annual deaths globally (400,000 in SSA) [4]. Because most of these deaths are among children and women, biomass use is directly or indirectly related to multiple Millennium Development Goals (MDGs), including environmental sustainability, reducing child mortality, and gender equity. As liquid biofuels such as ethanol and biodiesel expand in market share in developed nations, added pressures on these lands will develop, but so will market opportunities that could be used to reinvest in restorative land management practices and greater productivity for both domestic uses and for export.

A database was developed of current fuel use and a range of scenarios of household energy futures up to 2050 in SSA (Table 1). The dataset is based on current national-level energy production and consumption (Fig 1) which were estimated from the United Nations Food and Agriculture Organization's (FAO) forest products database and the International Energy Agency's (IEA) statistical database of non-OECD countries [2, 3]. The FAO records woodfuel production and trade from 41 countries in SSA, including separate estimates for charcoal.

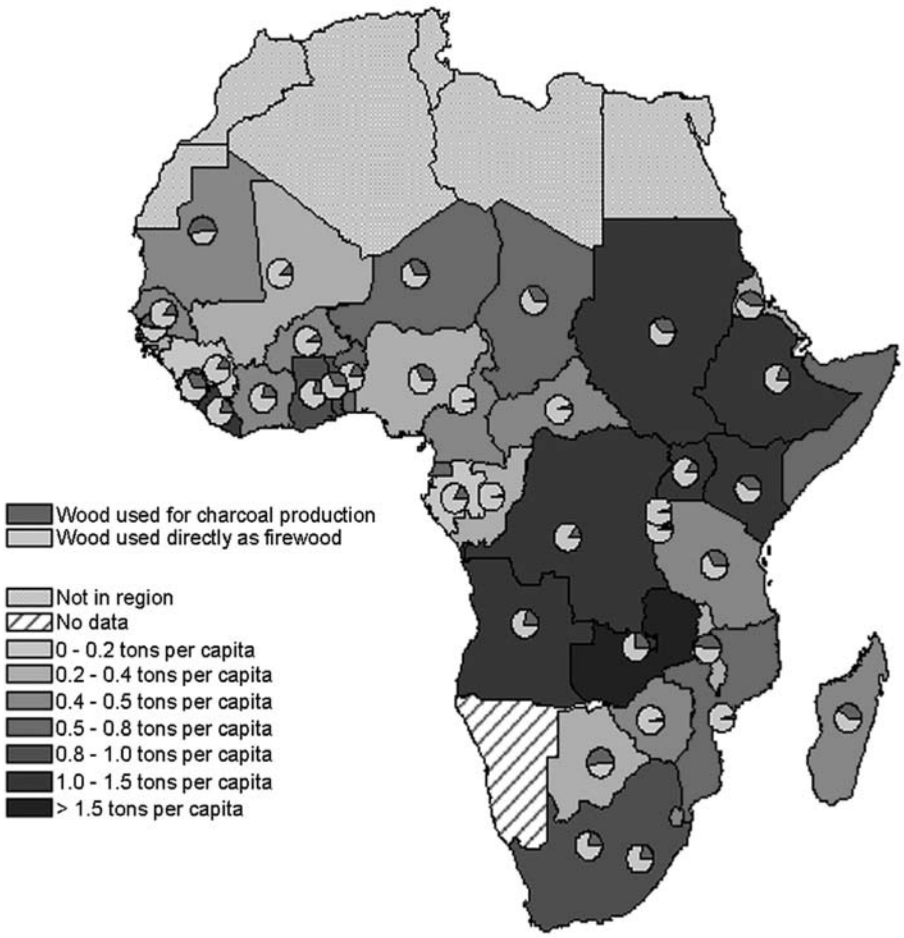

Figure 1: Current per-capita biomass production in SSA. The colors show total wood fuel consumption and the pie charts show the fraction of wood that is used for charcoal based on multiple sources. FAO biomass estimates (including charcoal) [3] were roughly consistent with IEA estimates and used for all countries except Angola, Kenya, South Africa, Sudan, and Zambia (20% of the region's population). For these countries FAO biomass estimates would have been too low to meet minimal household energy needs, when considered with energy use from fossil fuels and other energy sources reported by IEA [2]. In all of these countries except Kenya, IEA estimates were used; for Kenya, data from a detailed national household fuel consumption study was used [25].

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Table 1: Scenarios of household energy futures in SSA. All scenarios begin from the same 2000 baseline. In 2000, 64% of the population lived in rural areas. 41%, 34%, 13%, 8% and 4% of urban households used wood or crop residues, charcoal, kerosene, LPG and electricity as their primary source of household energy, respectively; 94%, 4%, and 2% of rural households used wood or crop residues, charcoal, and kerosene. Future population and urbanization estimates were from the United Nations Population Division. Future household energy use and production scenarios examine the role of two factors: household fuel choice and biomass harvesting and charcoal production techniques. The rate of adoption of alternative fuels and sustainability practices were also examined (gradual versus rapid scenarios).

Scenario	Household fuel choice pattern	Woodfuel harvest and charcoal production	Definitions
Group 1: Business as usual scenarios			
Business-as-usual (BAU)	Little change from current patterns in rural and urban areas	Unsustainable	The proportion of people in rural and urban areas using each fuel remains unchanged from the baseline year. However, differential rates of population growth and urbanization among different countries in the region result in regional changes in household fuel choice during the period of analysis. No changes occur in woodfuel harvesting practices or in charcoal production techniques, in which 20% of trees removed for charcoal and 80% of those removed for wood regenerate.
Sustainable BAU (BAU-S)		Fully sustainable by 2050	Identical fuel consumption as in BAU, but there is a gradual linear increase in the proportion of trees harvested sustainably as well as in the use of improved (high-efficiency) charcoal kilns. By 2050, tree regeneration reaches 80% for charcoal harvesting and 100% for firewood harvesting. Also by 2050, 100% of charcoal production takes place in high-efficiency kilns.
Group 2: Charcoal intensive scenarios			
Charcoal (C)	Large shift from wood to charcoal with minimal use of fossil fuels	Unsustainable	Between 2000 and 2050, there is a gradual linear transition from wood to charcoal in both urban and rural areas By 2050, the fraction of households using wood decreases by 40% in rural areas and 100% in urban areas, with both groups shifting to charcoal. As a result, in 2050 approximately 80% of urban households and 40% of rural households are using charcoal (61% of the total population). There are no changes in woodfuel harvest practices or in charcoal production methods.
Sustainable charcoal (C-S)		Fully sustainable by 2050	Identical trend in fuel consumption as in C, but there is a simultaneous shift in the fraction of harvested trees allowed to regenerate as well as in the use of improved (high-efficiency) charcoal kilns. By 2050, tree regeneration reaches 80% for charcoal production and 100% for firewood harvest; 100% of charcoal production takes place in high-efficiency kilns.
Rapid charcoal (RC)		Unsustainable	As in scenario C, the fraction of firewood users decreases by 40% in rural areas and by 100% in urban areas in as a result of a shift to charcoal. However, the switch occurs much more rapidly so that it is complete by 2010. In 2010, 40% of rural households and 75% of urban households use charcoal (52% of the total population). The rural and urban fractions remain constant through the rest of the analysis, but the total fraction of charcoal users continues to increase because of a demographic shift to urban areas. By 2050, the fraction of the total population using charcoal increases to 64%.
Rapid sustainable charcoal (RC-S)		Fully sustainable by 2010	Identical fuel consumption patterns as in RC, but there is also a rapid increase in the proportion of harvested trees allowed to regenerate as well as the use of improved (high-efficiency) charcoal kilns. The increase in tree re-generation and improved kilns is driven by a policy of aggressive dissemination of improved kiln technologies and improved land management. By 2010, tree regeneration reaches 80% for charcoal production and 100% for firewood harvest; 100% of charcoal production takes place in high-efficiency kilns.
Group 3: Fossil fuel intensive scenarios			
Fossil-fuel (F)	Large shift from wood and charcoal to petroleum-based fossil fuels	Unsustainable	Firewood and charcoal users in both urban and rural areas switch gradually to LPG and kerosene. By 2050, the proportion of households using wood or charcoal decreases by 40% in rural areas and 80% in urban areas. In rural areas, the shift is primarily to kerosene; in urban areas, the shift is to both kerosene and LPG. As a result, in 2050, 30% of households in rural areas use kerosene and 10% use LPG. In urban areas, 30% use kerosene and 50% use LPG. In total, 63% of the population uses fossil fuels.
Rapid fossil-fuel (RF)		Unsustainable	RF follows a similar pattern as scenario F, but at an accelerated pace. By 2010, approximately 40% of the rural population and 80% of the urban population (54% of total population) use fossil fuels. The rural and urban fractions remain constant up to 2050, but the total fraction of fossil fuel users continues to increase because of a demographic shift to urban areas. By 2050, the total fraction of people using fossil fuels increases from 54% to 63%.

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Charcoal is widely used in Africa, even in countries with large endowments of fossil fuels, such as Gabon, Angola, and Nigeria [2]. IEA maintains information on biomass and fossil fuels used in the residential sector from 20 countries in the region, and an aggregate estimate for the remaining 21 nations. The data were analysed for (i) consistency for each fuel type between FAO and IEA; and (ii) consistency across fuel types from IEA. It was found that in 2000, households in SSA consumed nearly 470 million tons of woodfuels (0.72 tons/capita) in the form of wood and charcoal. By comparison, the FAO estimates that India and China, with a combined population nearly 3.5 times larger, used 340 million tons of woodfuels in the same year.

The number of households using each fuel was derived from household welfare surveys conducted in the 1990s and compiled by the World Bank for 20 countries [5]. These nations covered 47% of the region's urban population and 63% of its rural population. For countries not surveyed, separate rural and urban population-weighted estimates from surveyed nations were applied. South Africa was excluded from the weighted averages, because it has a distinct pattern of household fuel consumption. These extrapolations are consistent with the observed low variability of fuel use patterns across the 20 countries with data, especially for rural areas which form 64% of SSA's population (excluding South Africa, the fraction of households using woodfuels varied from 86%-99% in rural areas and from 26%-96% in urban areas in the 20 countries with data) [5]. Overall, 94% of the African rural population and 73% of the urban population use woodfuels as their primary source of energy, mainly in the form of wood in rural areas and an equal split of wood and charcoal in urban centres. Most remaining households use a combination of kerosene, liquefied petroleum gas (LPG), and electricity [6].

The scenarios for future household energy sources and use (Table 1) examined the role of two factors: (i) household fuel choice (Fig 2) and (ii) sustainability of biomass harvesting and charcoal production techniques. Economic growth and energy infrastructure development have lagged in SSA relative to other world regions,

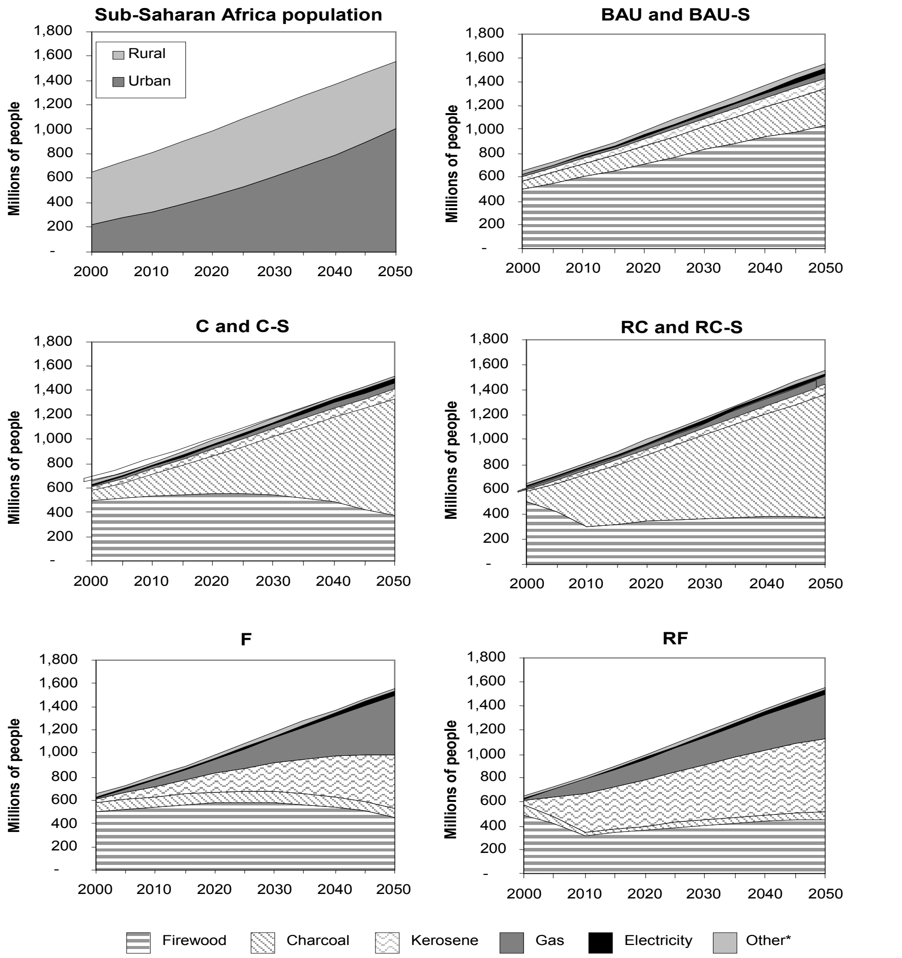

Figure 2: Number of people in SSA using each fuel in BAU, charcoal (C and RC), and fossil fuel (F and RF) scenarios. In C between 2000 and 2050, the absolute number of people using charcoal increases more than 10-fold, partly driven by population growth and urbanization and partly by a shift to charcoal. This is a large, but empirically realistic shift. For example, between 1980 and 2000, the number of households using charcoal as a primary source of energy in Kenya increased by about 250%, despite frequent attempts by the Kenyan government to restrict charcoal production [25]. "Other" includes crop residues, dung, and mineral coal.

limiting a large-scale shift to commercial sources of energy in the residential sector [7], which is presented in the business-as-usual scenario (BAU). Further, economic growth and infrastructure expansion do not automatically create a parallel and simultaneous shift to commercial energy for household needs. Even in China, where rapid economic growth and infrastructure expansion have contributed to near-universal electricity access [8], solid fuel use for cooking and heating among households has persisted; 80% of Chinese households continue to rely on biomass (mainly crop residues) and/or coal as their primary cooking and heating fuels [9].

In addition to the BAU trends, in which population growth and urbanization are the main drivers of change in household fuel choice, two additional categories of scenarios for household fuel use were examined. The first group examines a systematic shift from wood to charcoal (C and RC). Charcoal is a popular fuel in many countries in SSA because it is relatively clean, safe, affordable and storable, and requires no expensive equipment to use. The second group of scenarios envisions large-scale adoption of petroleum-based fossil fuels (kerosene and LPG), which are currently commercial alternatives to biomass fuels in many mid- and high-income nations (F and RF) [10]. Like charcoal, kerosene can be purchased in small quantities and can be used with relatively inexpensive equipment. It has a reasonably well-developed supply chain and is used throughout the region for lighting, as well as for cooking in urban areas. In contrast, LPG must be purchased in relatively large quantities and requires much more expensive stoves, both creating barriers to the urban poor and rural households. With the exception of Senegal, where there have been substantial efforts to promote LPG, its use is currently limited to wealthier urban families in a small number of countries

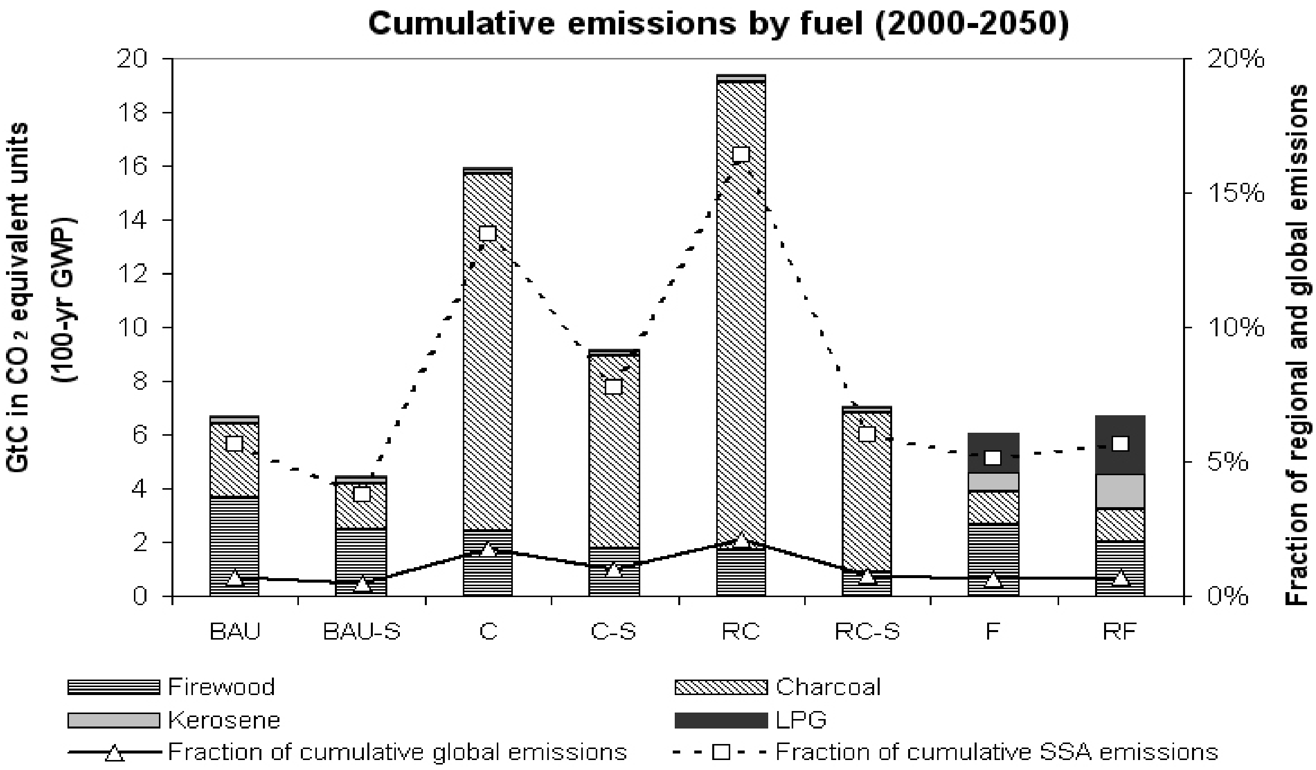

Figure 3. Cumulative GHG emissions from 2000 and 2050 from CO_2, CH_4, and N_2O converted to CO_2 equivalent units, weighted by 100-year-GWP for each scenario of SSA household energy futures. Totals are disaggregated by emissions from each fuel. The figure also shows cumulative emissions as fractions of regional and global cumulative emissions (118 GtC and 917 GtC respectively, based on the median emissions scenario reported in the Special Report on Emissions Scenarios (SRES) to inform policy makers during the IPCC's Third Assessment period [13]). See Fig S9 for annual emissions from each scenario. The figure presents the sum of emissions of GHGs targeted by the Kyoto Protocol (KP): CO_2, CH_4, and N_2O. This omits warming effects of carbon monoxide (CO), non-methane hydrocarbons (NMHCs), and aerosols or particulate matter (PM). These non-KP GHGs were included in sensitivity analysis along with analysis based on a 20-year GWP.

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[5, 8]. These characteristics were the basis for using distinct household fuel use patterns for rural and urban areas in our scenarios.

For each biomass-based scenario, the impacts were examined of sustainably harvested biomass and charcoal production technology on GHG emissions (BAU-S, C-S, and RC-S) (Table 1). Nearly all charcoal in SSA currently is produced in traditional kilns, with sub-optimal conversion efficiency and no emission controls. Technological shifts in the charcoal production include indigenous or exotic multipurpose tree crops, alternative inputs like biomass waste products, and efficient kilns with emission controls. For each scenario, the emissions were estimated of CO_2 and non-CO_2 GHGs from both the production and consumption of all fuels. Both charcoal and fossil fuels are associated with significant "upstream" (production) emissions. In contrast, wood has negligible upstream emissions. Both upstream and end-use emissions were converted into CO_2 equivalent units using 100-year Global Warming Potential (GWP) to account for the differential warming effect (radiative forcing) of each emitted GHG [11 - 13].

The net GHG emissions from residential energy use in SSA in 2000 were 79 MtC (61% from wood; 35% from charcoal; 3% from kerosene; and 1% from LPG). In the absence of systematic changes in fuel use patterns and in production and harvesting techniques (BAU scenario), cumulative emissions between 2000 and 2050 will be an estimated 6.7 GtC. The two fossil fuel-intensive scenarios (F and RF) have the second and third lowest cumulative emissions, after the BAU fuel scenario with sustainable harvesting and charcoal production (BAU-S). The highest estimated cumulative emissions were from two charcoal-intensive scenarios with unsustainable biomass harvesting and traditional, inefficient charcoal production (C and RC) (Fig 3). However, if these household fuel scenarios are accompanied with sustainable harvesting and a transition to cleaner and higher efficiency charcoal production technologies (C-S and RC-S), emissions will be reduced by 45% and 66% for gradual and rapid transitions.

The impacts of future fuel use scenarios were estimated on the two most common diseases associated with household fuel use: mortality from lower respiratory infections (LRI, mainly pneumonia) among children (< 5 years of age) and chronic obstructive pulmonary disease (COPD) among adult women. In 2000, there were 690,000 LRI deaths among children and 53,000 COPD deaths among adult females in SSA [14]. An estimated 51% of child LRI deaths (350,000 deaths) and 63% of adult female COPD deaths (34,000 deaths) were caused by household use of wood and charcoal [15]. Without systematic changes in urban and rural fuel use patterns, household biomass use will result in an estimated 8.1 million LRI deaths among young children and 1.7 million COPD deaths among adult women between 2000 and 2030 (50% of all childhood LRI deaths and 63% of all adult female COPD deaths in the 30-year interval) (Fig 4). Of these 9.8 million premature deaths, 1.0 and 1.3 million are avoidable with gradual transitions to charcoal (C) and fossil fuels (F), respectively; 2.8 and 3.7 million are avoidable with more rapid transitions to the two energy futures (RC and RF) [16]. 83-85% of avoidable deaths are in children, and the remaining among adult women.

This integrated assessment of GHG

emissions and the health impacts of household fuel use in sub-Saharan Africa, the world's poorest region with the lowest per-capita energy consumption and worst health status, reflects the substantial disease burden and GHG consequences of continuing current land and energy management practices. A shift to sustainable biomass harvesting without a shift in household fuel use patterns can reduce GHG emissions by 36%, but will have no health or direct welfare benefits for the region. Transition to petroleum-based fuels provides the next largest climate change benefits with substantial improvements in childhood and adult female mortality [10]. This transition is already underway among wealthier urban households in some countries of the region. However, for many people this is not a feasible option over the next 2-3 decades. Obstacles include fuel affordability for individual households, high capital costs for fuel processing and delivery infrastructure, as well as volatility in both price and supply as a consequence of national energy policies and international markets.

The sustainable charcoal scenarios presented here define alternatives for significant health benefits in SSA, while addressing regional and global environmental issues. A shift from firewood to either charcoal or fossil fuels can reduce indoor air pollution by 90% or more [17]. Therefore, charcoal can capture much of the health benefits of fossil-fuel use, without the economic burden and infrastructure requirements [18, 19]. In Kenya, the initial cost of a charcoal stove lasting 1-2 years is only \$3-5; LPG stoves and gas tanks cost \$30-50. In urban centres, where charcoal markets are well-developed and firewood must be purchased, the operating cost of charcoal stoves per unit of useful energy delivered is similar to wood, and substantially cheaper than fossil fuels [19]. Therefore, a shift to charcoal among sub-Saharan African households can be equal to or more cost-effective than some of the commonly cited health interventions in developing countries [14, 20]. Arguably more important, charcoal is already a preferred fuel among many consumers and has a well-established production and marketing network in place in many countries. Therefore, charcoal resolves the important concern about

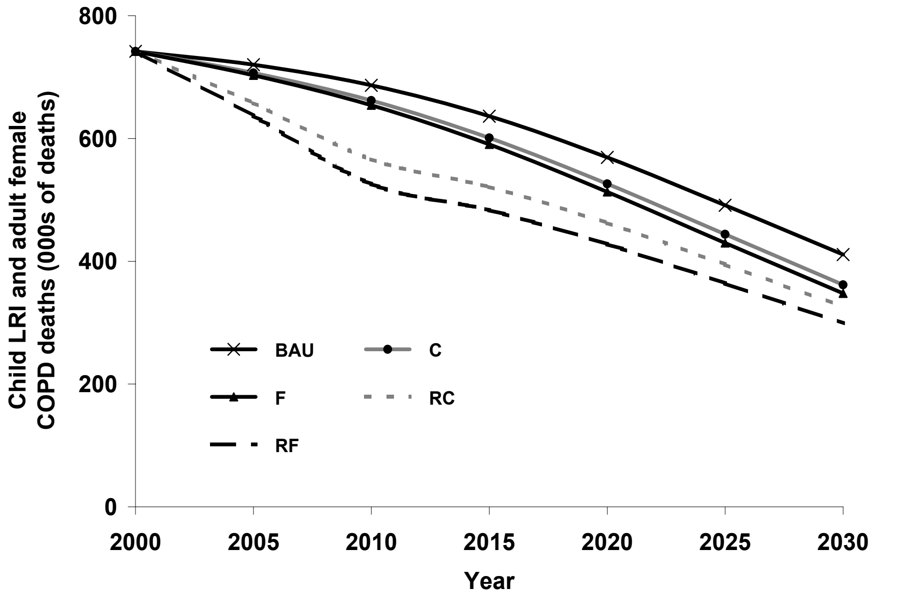

Fig. 4. Estimated mortality for scenarios of household energy futures in SSA. Diseases included are LRIs among children < 5 years of age and COPD among adult women. Estimates account for forecasted demographic change (population growth and aging) and secular trends in background disease and mortality levels. The observed secular (BAU) decline in childhood LRI mortality is a result of factors such as increased coverage and efficacy of pneumonia case management using antibiotics; increased awareness and practice of breastfeeding, which increases child immunity and survival; and other secular trends caused by economic and technological factors (29). Secular (BAU) trends in COPD are upward mainly because of population aging (COPD mortality increases with age). There has been a slight increase in age-specific COPD mortality rates at older ages, possibly due to small increases in smoking among women in Africa, and a slight decrease in age-specific rates in middle ages, possibly due to competing causes of death (mainly human immunodeficiency virus/acquired immunodeficiency syndrome). Similar directions are seen for lung cancer, another disease affected by smoking, which is the main driver of secular COPD rates in Africa. See Fig. S11 for separate estimates by disease.

"intervention scaling-up" in sustainable development and health technology evaluation.

Widespread charcoal use in Africa as a health intervention presents major policy and research challenges and opportunities. Fig 3 demonstrates that the widespread use of charcoal without changes in technology and land managements will lead to substantially higher GHG emissions – and has large, though poorly characterized, impacts on forest cover, soil fertility and biodiversity. Sustainable practices, similar to past efforts in Thailand and Brazil [21, 22], can substantially reduce these emissions. A real opportunity also exists to develop new harvesting and production methods, possibly with even less environmental impacts than those in the sustainable scenarios considered here (e.g. charcoal production from alternative feedstocks [23]; but this requires investment in technology R&D, and technology transfer and dissemination within and between countries. In addition to technological needs, the barriers to sustainable charcoal production are rooted in a lack of coherent energy policies specifically addressing residential energy needs and biases toward industrial energy resources, as well as outdated forest policies that put control of forest resources in the hands of centralized agencies, which rarely recognise energy as an important forest product. If these technological, funding and institutional challenges are met, transitioning to sustainable charcoal would create domestic jobs, boost rural economies, lessen the need for imported fossil fuels and save foreign exchange. This integration of health outcomes into energy and resource technologies and policies offers an opportunity to reduce child mortality, achieve gender equality, and promote environmental sustainability.

Notes and References

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6. In addition, approximately 3% of households in the region use non-woody biomass like crop residues or dung and, according to data from national censuses, approximately 3% of the combined population in South Africa, Zimbabwe and Botswana (about 0.4% of the regional population) rely on fossil coal.

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15. For comparison, in the same year in SSA, 1.8 million deaths were caused by protein-energy malnutrition.

16. The rapid transitions are particularly effective in reducing mortality for two reasons: (i) Transition to cleaner fuels has immediate benefits for child LRI mortality, because LRI is an acute disease. The projected secular trend of LRI mortality in SSA is declining, mainly because of expectations of improved access to clinical case management using antibiotics (30).

17. Reductions refer to particulate matter, the pollutant consistently associated with the most substantial negative health impacts (30). Carbon monoxide (CO) is also a harmful pollutant associated with biomass fuels. In measurement in Kenya, CO concentrations from charcoal were not significantly different than those from wood stoves (30). Promoting charcoal as a household fuel should be accompanied with education about safe practices.

18. Under a specific definition, gradual and rapid transitions to ceramic wood-stoves would avoid 400,000 and 1.2 million deaths; gradual and rapid transitions to mixed fossil and biomass fuels would avoid 900,000 and 2.8 million deaths. Well-designed and well-maintained ventilated stoves with chimney may provide health benefits that are comparable to charcoal, but they have not been widely disseminated in Africa.

19. The cost of cooking with wood is highly variable because wood can be obtained for free, though in urban areas this not usually the case. Market prices for split fuel wood (reported in 25) indicate that annual cooking costs would be at least $200 if all wood were purchased. For comparison, using a combination of field observations and fuel prices reported in (25), we estimate a range of annual cooking costs for charcoal ($116-271), kerosene ($149-273), LPG ($274-374) and electricity ($230-467). The range in costs is a function of fuel prices, which depend on the quantity purchased, the cost of the stove (amortized over its expected lifetime using a 12% discount rate), and stove efficiencies (reported, for example, in 31).

20. Interventions with particularly large benefits include oral rehydration therapy, insecticide-treated bednets, clean water and sanitation, antibiotics for pneumonia, micronutrient supplementation, and exclusive breastfeeding (32). If the same assumption of 99% coverage is applied, in 2000, charcoal (99% of current wood users switching to charcoal) would save 250,000 childhood LRI deaths (6% of all SSA child deaths) and petroleum-based fossil fuels (99% of all biomass users) 350,000 childhood LRI deaths (8% of all SSA child deaths).

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23. Charcoal can be made from many forms of biomass including agricultural and timber processing residues. There are some attempts to market such products in several countries in SSA, but market penetration is currently very low.

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