[the Wonoka Formation (*33*)] and the western United States [Rainstorm Member, Johnnie Formation (*34*)] but chose to equate it with a postulated Gaskiers-related $\delta^{13}C$ excursion from circa 580 Ma (*35*). Instead, our data indicate that this globally correlated negative $\delta^{13}C$ excursion is not related to any known glaciation (*36*). The duration of this excursion is unconstrained; however, given that it is captured within over 100 m of section in Oman (Fig. 1) combined with approximate sediment accumulation rates calculated with our constraints, we suggest a duration of >1 and <10 My.

The Doushantuo and correlative strata record a fundamental shift from an interval of large carbon isotopic anomalies corresponding to glacial episodes (750 to 580 Ma) to an interval of anomalies unrelated to obvious glacial episodes (i.e., the anomalies from circa 551 and 542 Ma), as well as subsequent large fluctuations in the lower Cambrian. These new geochronological data allow us to calibrate that shift as being synchronous with the appearance of larger and more complex metazoans; this suggests possible feedback relationships between evolutionary innovation and seawater chemistry (Fig. 2).

Our ages indicate that the Doushantuo Formation spans more than 90% of the Ediacaran Period. These constraints are consistent with the upper Doushantuo/Shuram/Kuibis excursion being broadly coincident with the first appearance of complex trace fossils and mollusk-like bilaterian *Kimberella* (*37*), dated as slightly older than 555.1 ± 1.0 Ma (*24*). The advent of large pelagic bilaterians with unidirectional guts would have increased the flux of organic carbon to the deep ocean (*38*). Additionally, the radiation of algae containing resistant biopolymers in cell wall and cysts (i.e., Miaohe Biota) and the advent of biomineralization (*Namacalathus* and *Cloudina*, >549 Ma) would have also resulted in an increased organic carbon and carbonate carbon flux (*39*). These changes would have resulted in a downward flux of organic carbon with a possible coupled oxidation of the organic reservoir (*38*, *39*) driving the negative $\delta^{13}C$ excursion. This feedback loop would lead to an increase in marine oxygen levels and stimulate productivity and inferentially predation. It may be no coincidence that the first reefs inhabited by abundant weakly calcified and rare fully calcified metazoans appeared at about the same time as the isotopic anomaly [i.e., before 549 Ma in Namibia (*6*, *40*)].

References and Notes

1. M. Y. Zhu *et al.*, *Prog. Nat. Sci.* **13**, 951 (2003).
2. J. Y. Chen *et al.*, *Science* **305**, 218 (2004).
3. S. H. Xiao, Y. Zhang, A. H. Knoll, *Nature* **391**, 553 (1998).
4. S. H. Xiao, X. L. Yuan, M. Steiner, A. H. Knoll, *J. Paleontol.* **76**, 347 (2002).
5. C. M. Zhou *et al.*, *Geology* **32**, 437 (2004).
6. J. P. Grotzinger, S. A. Bowring, B. Z. Saylor, A. J. Kaufman, *Science* **270**, 598 (1995).
7. R. J. F. Jenkins, J. A. Cooper, W. Compston, *J. Geol. Soc. London* **159**, 645 (2002).
8. G. H. Barfod *et al.*, *Earth Planet. Sci. Lett.* **201**, 203 (2002).
9. D. F. Chen, W. Q. Dong, B. Q. Zhu, X. P. Chen, *Precambrian Res.* **132**, 123 (2004).
10. Materials and methods are available as supporting material on *Science* Online.
11. Age uncertainties are stated at the 2σ level.
12. J. D. Yang, W. G. Sun, Z. Z. Wang, Y. S. Xue, X. C. Tao, *Precambrian Res.* **93**, 215 (1999).
13. G. Jiang, M. J. Kennedy, N. Christie-Blick, *Nature* **426**, 822 (2003).
14. M. Macouin *et al.*, *Earth Planet. Sci. Lett.* **224**, 387 (2004).
15. P. F. Hoffman, D. P. Schrag, *Terra Nova* **14**, 129 (2002).
16. This corresponds to approximate sediment accumulation rates of about 1.5 to 3 m/My.
17. G. P. Halverson, P. F. Hoffman, D. P. Schrag, A. C. Maloof, A. H. N. Rice, *Geol. Soc. Am. Bull.*, in press.
18. K.-H. Hoffmann, D. J. Condon, S. A. Bowring, J. L. Crowley, *Geology* **32**, 817 (2004).
19. This is the analytical uncertainty on the U-Pb concordia age (excluding tracer calibration uncertainty) calculated from Hoffmann *et al.* (*18*).
20. P. F. Hoffman, A. J. Kaufman, G. P. Halverson, D. P. Schrag, *Science* **281**, 1342 (1998).
21. W. Wang *et al.*, *Acta Micropalaeontol. Sin.* **19**, 382 (2002).
22. S. H. Xiao *et al.*, *Precambrian Res.* **130**, 1 (2004).
23. G. M. Narbonne, J. G. Gehling, *Geology* **31**, 27 (2003).
24. M. W. Martin *et al.*, *Science* **288**, 841 (2000).
25. D. Grazhdankin, *Paleobiology* **30**, 203 (2004).
26. S. Bowring, P. Myrow, E. Landing, J. Ramezani, J. Grotzinger, *Geophys. Res. Abstr.* **5**, 13219 (2003).
27. The Schwarzrand Subgroup is characterized by a +2 plateau (*6*,*28*). In the northern subbasin, the underlying Kuibis Subgroup records a decrease from +3 down to 0 in upper Mooifontein Member with values of –3 obtained on carbonates from the underlying Mara Member. In the southern subbasin the Kuibis Subgroup has values of about 0 at the top that gradually increase toward the bottom of the section to +4 and then decrease down to –1.
28. B. Z. Saylor, A. J. Kaufman, J. P. Grotzinger, F. Urban, *J. Sediment. Res.* **68**, 1223 (1998).
29. J. E. Amthor *et al.*, *Geology* **31**, 431 (2003).
30. S. J. Burns, A. Matter, *Eclogae Geol. Helv.* **86**, 595 (1993).
31. A. Cozzi, J. P. Grotzinger, P. A. Allen, *Geol. Soc. Am. Bull.* **116**, 1367 (2004).
32. P. A. Allen *et al.*, in *16th International Sedimentological Congress Abstract Volume* (International Association of Sedimentologists, Johannesburg, South Africa, 2002), pp. 7–8.
33. C. R. Calver, *Precambrian Res.* **100**, 121 (2000).
34. F. A. Corsetti, A. J. Kaufman, *Geol. Soc. Am. Bull.* **115**, 916 (2003).
35. P. M. Myrow, A. J. Kaufman, *J. Sediment. Res.* **69**, 784 (1999).
36. G. Q. Jiang, L. E. Sohl, N. Christie-Blick, *Geology* **31**, 917 (2003).
37. M. A. Fedonkin, B. M. Waggoner, *Nature* **388**, 868 (1997).
38. G. A. Logan, J. M. Hayes, G. B. Hieshima, R. E. Summons, *Nature* **376**, 53 (1995).
39. D. H. Rothman, J. M. Hayes, R. E. Summons, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 8124 (2003).
40. R. A. Wood, J. P. Grotzinger, J. A. D. Dickson, *Science* **296**, 2383 (2002).

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Mortality and Greenhouse Gas Impacts of Biomass and Petroleum Energy Futures in Africa

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We analyzed the mortality impacts and greenhouse gas (GHG) emissions produced by household energy use in Africa. Under a business-as-usual (BAU) scenario, household indoor air pollution will cause an estimated 9.8 million premature deaths by the year 2030. Gradual and rapid transitions to charcoal would delay 1.0 million and 2.8 million deaths, respectively; similar transitions to petroleum fuels would delay 1.3 million and 3.7 million deaths. Cumulative BAU GHG emissions will be 6.7 billion tons of carbon by 2050, which is 5.6% of Africa's total emissions. Large shifts to the use of fossil fuels would reduce GHG emissions by 1 to 10%. Charcoal-intensive future scenarios using current practices increase emissions by 140 to 190%; the increase can be reduced to 5 to 36% using currently available technologies for sustainable production or potentially reduced even more with investment in technological innovation.

Biomass fuels (wood, charcoal, dung, and agricultural residues) are vital to basic welfare and economic activity in developing nations, especially in sub-Saharan Africa (SSA), where they meet more than 90% of household energy needs in many nations. Combustion of biofuels emits pollutants that currently cause over 1.6 million annual deaths globally (400,000 in SSA) (*1*). Because most of these deaths are among children and women, biomass use is directly or indirectly related to multiple Millennium Development Goals of the United Nations (UN), including environmental sustainability, reducing child mortality, and gender equity.

We developed a database of current fuel use and a range of scenarios of household energy futures up to 2050 in SSA (Table 1). Current national-level energy production and consumption (Fig. 1) were estimated from the UN Food and Agriculture Organization's (FAO's) forest products database and the International Energy Agency's (IEA's) statistical database of countries not in the Organisation for Economic Cooperation and Development (*2*, *3*). FAO records woodfuel (defined as wood or wood transformed into charcoal) production and trade from 41 countries in SSA, including separate estimates for charcoal. 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 sectors of 20 countries in the region and an aggregate estimate for the remaining countries in the region. Data were analyzed for consistency of each fuel type between FAO and IEA and for consistency across fuel types from IEA (*4*). We estimated that in 2000, households in SSA consumed nearly 470 million tons of woodfuels (0.72 tons per capita) in the form of wood and charcoal. By comparison, FAO estimates that India and China, with a combined population nearly 3.5 times larger than that of SSA, used 340 million tons of woodfuels in the same year (*5*).

The fraction of households using each fuel was derived from nationally representative household-welfare surveys conducted in the 1990s and compiled by the World Bank for 20 countries (*4*, *6*). These nations contained 47% of the region's urban population and 63% of its rural population. For countries not surveyed, we applied population-weighted estimates from surveyed nations, separately for rural and urban populations. 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 to 99% in rural areas and from 26 to 96% in urban areas in the 20 countries with data) (*6*). 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 centers. Most remaining households use a combination of kerosene, liquefied petroleum gas (LPG), and, to a very limited extent, electricity (*7*).

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 compared with other world regions, limiting a large-scale shift to commercial sources of energy in the residential sector (*8*), which we present in the business-as-usual (BAU) scenario. Furthermore, 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 access to electricity (*9*), 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 (*10*).

In addition to the secular BAU trends, in which population growth and urbanization are the main drivers of change in household fuel use, we examined two additional categories of scenarios for household fuel choice. The first group examines a systematic shift from wood to charcoal (C, charcoal; RC, rapid charcoal). 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, fossil fuel; RF, rapid fossil fuel) (*11*). Like charcoal, kerosene can be purchased in small quantities and 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

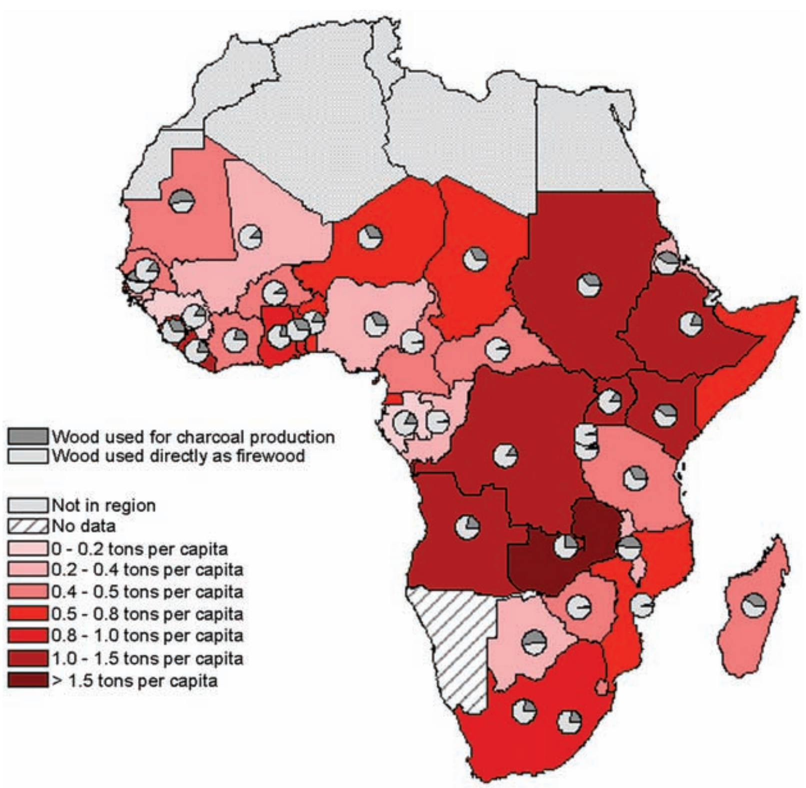

Fig. 1. Current per-capita biomass production in SSA. The colors show total wood fuel consumption, and the pie charts show the fraction of wood that is used for charcoal, based on multiple sources. FAO biomass estimates (including charcoal) (*3*) were roughly consistent with IEA estimates and were used 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 were used (*26*).

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Table 1. Scenarios of household energy futures in SSA. All scenarios begin from the same year 2000 baseline. In 2000, 64% of the population lived in rural areas. Forty-one, 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 are from the UN Population Division (*30*). Future household energy use and production scenarios examine the role of two factors: (i) household fuel choice and (ii) 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)	No change from current patterns in rural and urban areas of each country	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 in 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 (*4*).
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 use 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 regeneration 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%.

stoves, both of which are barriers to its use in the urban poor and rural households. The use of LPG is currently limited to wealthier urban families in a small number of countries, with the exception of Senegal, where there have been substantial efforts to promote LPG use (*6*, *9*). These characteristics were the basis for choosing distinct household fuel-use patterns for rural and urban areas in our scenarios.

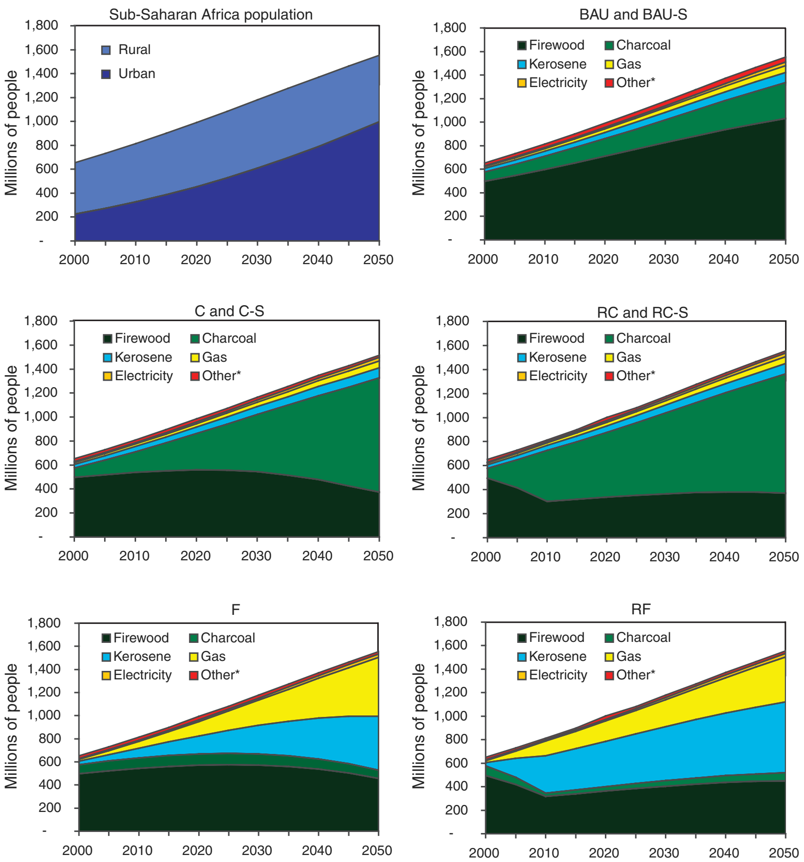

Fig. 2. Number of people in SSA using each fuel in BAU, charcoal (C and RC), and fossil fuel (F and RF) scenarios. For C between 2000 and 2050, the absolute number of people using charcoal increases more than 10-fold, partly driven by population growth and urbanization and partly by a shift to charcoal. 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 (*26*). "Other" includes crop residues, dung, and mineral coal. Rural-urban breakdown until 2030 is based on UN estimates, and after 2030 is based on projections (*4*, *30*).

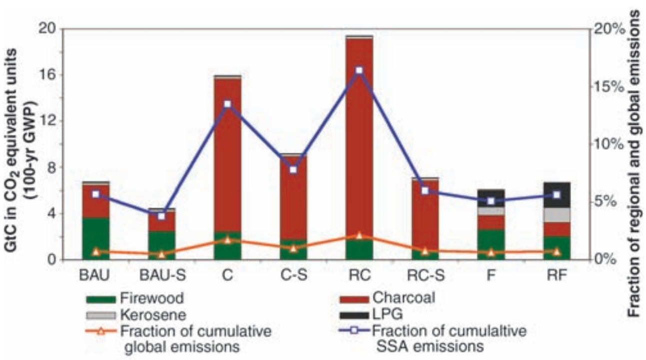

Fig. 3. Cumulative GHG emissions from 2000 and 2050 from CO_2, CH_4, and N_2O converted to CO_2 equivalent units, weighted by 100-year GWP for each scenario of household energy futures. Totals are disaggregated by emissions from each fuel. The figure also shows cumulative emissions as fractions of regional and global cumulative emissions [118 GtC and 917 GtC, respectively, based on the median emissions scenario reported in the Special Report on Emissions Scenarios to inform policy makers during the Intergovernmental Panel on Climate Change's Third Assessment period (*13*)]. See fig. S5 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 the warming effects of CO, non-methane hydrocarbons, and aerosols or particulate matter. These nonKP GHGs were included in the sensitivity analysis, along with sensitivity analysis based on a 20-year GWP (*4*).

For each biomass-based scenario, we examined the impacts of sustainably harvested (S) biomass (*4*) and charcoal production technology on greenhouse gas (GHG) emissions (BAU-S, C-S, and RC-S) (Table 1). Nearly all charcoal in SSA currently is produced in traditional kilns, which have suboptimal conversion efficiency and no emission controls. Technological shifts in charcoal production include indigenous or exotic multipurpose tree crops, alternative inputs such as biomass waste products, and efficient kilns with emission controls. For each scenario, we estimated emissions of CO_2 and non-CO_2 GHGs from both 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 (*4*, *12–14*).

The net GHG emissions from residential energy use in SSA in 2000 were 79 million tons of carbon (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 by 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, respectively.

We also estimated the impacts of future fuel-use scenarios on the two most common diseases associated with household fuel use: mortality from lower respiratory infections (LRIs, 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 (*15*). 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 (*4*, *16*). 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 of 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). 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) (*17*). Eighty-three to 85% of avoidable deaths are in children, and the remaining are among adult women (Fig. 4).

This integrated assessment of GHG emissions and health impacts of the household fuel use in SSA, the world's poorest region with the lowest per-capita energy consumption and worst health status, reflects the substantial disease burden and GHG consequences if current land- and energy-management practices continue. 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 reductions in childhood and adult female mortality (*11*). 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 to 3 decades. Obstacles include fuel affordability for individual households, high capital costs for fuel processing and delivery infrastructure, and 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 and address regional and global environmental issues. A shift from firewood to either charcoal or fossil fuels can reduce indoor air pollution by 90% or more (*18*). Therefore, charcoal can capture much of the health benefits of fossil-fuel use without the economic burden and infrastructure requirements (*19*, *20*). In Kenya, the initial cost of a charcoal stove lasting 1 to 2 years is only \$3 to \$5; LPG stoves and gas tanks cost \$30 to \$50. In urban centers, 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 that of wood and substantially cheaper than fossil fuels (*20*). Therefore, a shift to charcoal among SSA households can be equally as or more cost effective than some of the commonly cited health interventions in developing countries (*15*, *21*). 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 "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. Widespread use of charcoal without changes in technology and land management will lead to substantially higher GHG emissions (Fig. 3). Charcoal use has large, though poorly characterized, impacts on forest cover, soil fertility, and biodiversity. Currently feasible sustainable practices, similar to past efforts in Thailand and Brazil (*22*, *23*), can substantially reduce these emissions. A real opportunity also exists to develop new harvesting and production methods, possibly with even fewer environmental impacts than those in the sustainable scenarios considered here (e.g., charcoal production from alternative feedstocks) (*24*). However, these advances require investment in technology R&D and in 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 in 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 recognize 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, promote gender equality, and improve environmental sustainability.

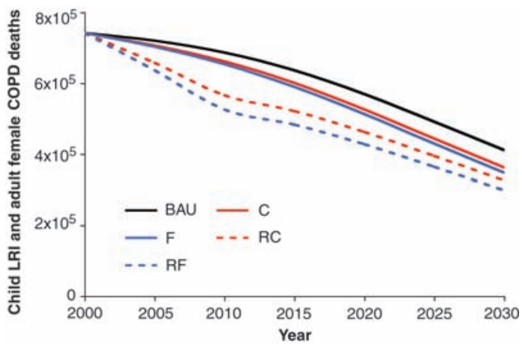

Fig. 4. Estimated mortality for scenarios of household energy futures in SSA. Diseases included are LRIs among children <5 years of age and COPD among adult women. Estimates account for forecasted demographic change (population growth and aging) and secular trends in background disease and mortality 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.

References and Notes

1. M. Ezzati *et al.*, *Lancet* **360**, 1347 (2002).
2. IEA, *Energy Statistics of Non-OECD Countries* (IEA Publications, Paris, 2004).
3. FAOSTAT data (UN FAO, 2004) are available at http://faostat.fao.org/faostat/collections?version=ext&hasbulk=0&subset=forestry.
4. Materials, methods, and sensitivity analyses are available as supporting material on *Science* Online.
5. This estimate for China and India applies to woodfuels only. Households in China and India use more solid fuels than households in SSA but in forms other than woody biomass. In China, crop residues are common fuels in rural areas, and in India, crop residues and dung are each used by roughly 10% of households (*25*). Many households in China and India use coal as their primary fuel, which is also important for health and GHG impacts (*10*).
6. World Bank, *Africa Development Indicators Series* (World Bank, Washington, DC, 2000 and 2004).
7. In addition, approximately 3% of households in the region use nonwoody biomass such as 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) relies on fossil coal.
8. S. Karekezi, *Energy Policy* **30**, 915 (2002).
9. IEA, in *World Energy Outlook* (IEA Publications, Paris, 2002), pp. 365–407.
10. K. R. Smith, S. Mehta, M. Maeusezahl-Feuz, in *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, M. Ezzati, A. Lopez, A. Rodgers, C. Murray, Eds. [World Health Organization (WHO), Geneva, 2004], pp. 1435–1493.
11. K. R. Smith, *Science* **298**, 1847 (2002).
12. Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001).
13. R. Bailis, M. Ezzati, D. Kammen, *Environ. Sci. Technol.* **37**, 2051 (2003).
14. T. Bond, C. Venkataraman, O. Masera, *Energy Sustainable Dev.* **8**, 20 (2004).
15. WHO, *World Health Report 2002: Reducing Risk, Promoting Health Life* (WHO, Geneva, 2002).
16. For comparison, in the same year in SSA, 1.8 million deaths were caused by protein-energy malnutrition; 270,000 by iron deficiency anemia; 470,000 by vitamin A deficiency; 390,000 by zinc deficiency; 610,000 by unsafe water, sanitation, and hygiene; and 960,000 by malaria (*1*, *15*). Most of these deaths were among children and women. Deaths caused by individual risk factors are not additive because of multicausality. Recent studies have established exposure to biomass smoke during pregnancy as a risk factor for low birth weight (*27*, *28*). Although this relationship requires further confirmation and better quantification, if even a small fraction of the 260,000 low–birth weight deaths in SSA are caused by biomass use, it would increase the total disease burden substantially.
17. The rapid transitions are particularly effective in reducing mortality for two reasons. First, the 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 (*29*). Therefore rapid transitions to cleaner fuels promptly save lives when the background rates are at their worst (i.e., in the early part of the projection period). Second, rapid transition to cleaner fuels also reduces adult female deaths from COPD significantly. Because COPD is a chronic disease, the health benefits of cleaner fuels accrue gradually over time (fig. S10). With rapid transitions to clean fuels, a larger number of adult women will witness complete benefits by 2030. Coupled with the increasing number of older women in Africa because of population growth and aging (*30*), the benefits of rapid transition in reducing COPD are amplified in the later part of the projection period.

18. These are reductions in particulate matter, which is the pollutant consistently associated with the most substantial negative health impacts (*31*). Carbon monoxide (CO) is also a harmful pollutant associated with biomass fuels. In measurements in Kenya, CO concentrations from charcoal were not significantly different from those from wood stoves (*31*). Promoting charcoal as a household fuel should be accompanied with education about safe practices.
19. In practice, a large number of future energy paths may be taken. Examples include transitions to improved ceramic wood stoves among wood users and to mixed fossil and biomass fuels among biomass users. Because ceramic stove and mixed-fuel use are less precisely defined alternatives, both interventions have substantial heterogeneity in health hazards. Under a specific definition, gradual and rapid transitions to ceramic wood stoves would avoid 400,000 and 1.2 million deaths, respectively; 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 chimneys may provide health benefits that are comparable to those from charcoal, but they have not been widely disseminated in Africa.
20. The cost of cooking with wood is highly variable because wood can be obtained for free, although in urban areas this not usually the case. Market prices for split fuel wood (*26*) 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 (*26*), we estimate a range of annual cooking costs for charcoal (\$116 to \$271), kerosene (\$149 to \$273), LPG (\$274 to \$374), and electricity (\$230 to \$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 (*32*)].
21. Estimates of child deaths that could have been avoided worldwide in 2000 if the coverage of a number of nutritional, environmental, and treatment interventions were increased to 99% of children at need show that various interventions ranged between 1 and >10% (*33*). Interventions with particularly large benefits include oral rehydration therapy, insecticide-treated bed nets, clean water and sanitation, antibiotics for treating pneumonia, micronutrient supplementation, and exclusive breastfeeding (*33*). 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) would save 350,000 childhood LRI deaths (8% of all SSA child deaths).
22. K. R. Smith *et al.*, *Greenhouse Gases from Small-Scale Combustion in Developing Countries: Charcoal Kilns in Thailand* [Technical Report No. EPA-600/R-99-109, U. S. Environmental Protection Agency (EPA), Washington, DC, 1999].
23. O. C. Ferreira, *Economy and Energy* **20** (May-June 2000).
24. 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.
25. Government of India, *Census of India: 2001* (Central Statistical Office, Delhi, 2001).
26. Ministry of Energy (Kenya), *Study on Kenya's Energy Demand, Supply and Policy Strategy for Households, Small Scale Industries and Service Establishments: Final Report* (KAMFOR Company Limited, Nairobi, 2002).
27. E. Boy, N. Bruce, H. Delgado, *Environ. Health Perspect.* **110**, 109 (2002).
28. V. Mishra, X. Dai, K. R. Smith, L. Mika, *Ann. Epidemiol.* **14**, 740 (2004).
29. C. J. L. Murray, A. D. Lopez, in *The Global Burden of Disease*, C. J. L. Murray, A. D. Lopez, Eds. (Harvard School of Public Health on behalf of WHO and World Bank, Boston, 1996), pp. 325–395.
30. UN, *World Population Prospects: The 2002 Revision* (Population Division of the Department of Economic and Social Affairs of the UN Secretariat, 2004) available at www.un.org/popin/data.html.
31. M. Ezzati, B. Mbinda, D. Kammen, *Environ. Sci. Technol.* **34**, 578 (2000).
32. K. R. Smith *et al.*, *Greenhouse Gases From Small-Scale Combustion Devices in Developing Countries Phase IIa: Household Stoves in India* (Technical Report No. EPA-600/R-00-052, EPA, Washington, DC, 2000) available at: www.teriin.org/climate/emission.htm.
33. G. Jones *et al.*, *Lancet* **362**, 65 (2003).
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A Late Jurassic Digging Mammal and Early Mammalian Diversification

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A fossil mammal from the Late Jurassic Morrison Formation, Colorado, has highly specialized teeth similar to those of xenarthran and tubulidentate placental mammals and different from the generalized insectivorous or omnivorous dentitions of other Jurassic mammals. It has many forelimb features specialized for digging, and its lumbar vertebrae show xenarthrous articulations. Parsimony analysis suggests that this fossil represents a separate basal mammalian lineage with some dental and vertebral convergences to those of modern xenarthran placentals, and reveals a previously unknown ecomorph of early mammals.

The Late Jurassic was a time of rapid diversification of mammals. Insectivorous eutriconodontans, symmetrodontans, and dryolestoids, and the omnivorous multituberculates dominated the Late Jurassic mammalian faunas of Laurasia, displacing several more primitive mammaliaform lineages (*1*–*3*). Most mammals of the Jurassic and Early Cretaceous with preserved skeletal elements are generalized terrestrial mammals (*4*–*7*), except docodontans (*2*). Here, we report a new mammal with dental specializations like those known only from early Tertiary palaeanodonts and extant xenarthran and tubulidentate placental mammals, in addition to numerous fossorial (digging) skeletal features.

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Fruitafossor windscheffeli gen. et sp. nov. (*8*) is represented by relatively complete lower jaws (Fig. 1), incomplete cranium, and nearly 40% of the postcranial skeleton, including complete forelimb and manus (Fig. 2), several elements of the hindlimb and hindfoot (pes) (Fig. 3), and most of the thoracic, complete lumbar and sacral, and some caudal vertebrae. The new taxon is distinguishable from all known Mesozoic mammaliaforms in having tubular and single-rooted molars with open-ended roots (Fig. 1) and in that the molar crown lacks enamel. It differs from all known Mesozoic mammaliaforms in that the posterior opening of the mandibular canal is located anterior to the pterygoid crest in a broad meckelian groove. It differs from all Jurassic mammals (except *Hadrocodium*) (*9*) in having an inflected mandibular angle that is continuous with the pterygoid crest (Fig. 1). *Fruitafossor* is also distinguishable from and more primitive than the well-established and successively more inclusive hierarchies of eutherians (*10*, *11*), the crown therian clade of eutherians and metatherians (*7*, *12*, *13*), the trechnotherian clade (*Zhangheotherium* and crown therians) (*14*–*17*), and the theriiform clade (multituberculates and trechnotherians) (*18*), and is more plesiomorphic (*19*, *20*) than each of these clades by many characteristics.