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The carbon footprint of traditional woodfuels

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Over half of all wood harvested worldwide is used as fuel, supplying ∼9% of global primary energy. By depleting stocks of woody biomass, unsustainable harvesting can contribute to forest degradation, deforestation and climate change. However, past efforts to quantify woodfuel sustainability failed to provide credible results. We present a spatially explicit assessment of pan-tropical woodfuel supply and demand, calculate the degree to which woodfuel demand exceeds regrowth, and estimate woodfuel-related greenhouse-gas emissions for the year 2009. We estimate 27–34% of woodfuel harvested was unsustainable, with large geographic variations. Our estimates are lower than estimates from carbon offset projects, which are probably overstating the climate benefits of improved stoves. Approximately 275 million people live in woodfuel depletion 'hotspots'—concentrated in South Asia and East Africa—where most demand is unsustainable. Emissions from woodfuels are 1.0–1.2 Gt CO_2e yr^{-1} (1.9–2.3% of global emissions). Successful deployment and utilization of 100 million improved stoves could reduce this by 11–17%. At US$11 per tCO_2e, these reductions would be worth over US$1 billion yr^{-1} in avoided greenhouse-gas emissions if black carbon were integrated into carbon markets. By identifying potential areas of woodfuel-driven degradation or deforestation, we inform the ongoing discussion about REDD-based approaches to climate change mitigation.

Traditional woodfuels, which include both firewood and charcoal used for cooking and heating, represent approximately 55% of global wood harvest and 9% of primary energy supply[1,2]. The current extent and future evolution of traditional woodfuel consumption is closely related to several key challenges to sustainable development. Roughly 2.8 billion people worldwide[3], including the world's poorest and most marginalized, burn wood to satisfy their basic energy needs. Woodfuels can impact public health[4], cause deforestation or forest degradation[5], and contribute to climate change[6–8]. Climate impacts arise from two pollutant flows: CO_2 is emitted because a fraction of woodfuel is harvested unsustainably; methane (CH_4), black carbon and other short-lived climate forcers (SLCFs) are emitted because of incomplete combustion, which also emits health-damaging pollutants. Thus, woodfuels present society with two important links between local and global impacts; incomplete combustion releases pollutants that damage health and warm the atmosphere, and unsustainable harvesting drives both forest degradation and climate change.

Risks to public health are increasingly well characterized[4], whereas impacts on deforestation, degradation and global climate remain highly uncertain. Historically, woodfuel demand was considered a major driver of land cover change[9,10] (LCC). However, early research failed to account for regrowth, consumers' response to scarcity, and use of trees outside forests[11,12]. More recent local or regional assessments find conflicting results[13–17], suggesting that geography is an important determinant of woodfuel sustainability. However, few systematic studies of woodfuel sustainability and greenhouse gas (GHG) emissions have been conducted[18]. The Intergovernmental Panel on Climate Change's Fourth Assessment claimed that 10% of global woodfuel is harvested unsustainably[19,20], and the Fifth Assessment stresses that net emissions from woodfuels are unknown[17]. Better understanding of the contribution of woodfuels to deforestation, forest degradation and climate change is needed to evaluate the impact of the growing wave of household energy interventions and inform emerging REDD (Reducing Emissions from Deforestation and Forest Degradation) methodologies[21,22].

Here we present a spatially explicit snapshot of woodfuel supply and demand (Supplementary Section 1) throughout tropical regions where traditional woodfuel consumption is concentrated. Using 2009 as a base year, we quantify the extent to which woodfuel demand exceeds supply, identify specific 'hotspots' where harvesting rates are likely to cause degradation or deforestation, quantify the carbon emissions that result from current woodfuel exploitation, and estimate the emission reductions that could be achieved from large-scale interventions[23].

Nearly all landscapes produce a measurable increment of woody biomass either as new growth or as regrowth from previous disturbances. This assessment considers supply/demand balance over one year. If an area is harvested for woodfuel below the annual growth rate, then woody biomass stocks are not depleted and harvesting is sustainable. However, if annual harvesting exceeds incremental growth, it is unsustainable, leading to a decline of woody biomass, forest degradation and net carbon emissions. In this assessment, we define the wood harvested in excess of the incremental growth rate as non-renewable biomass[24] (NRB).

Pan-tropical woodfuel supply and demand

We treat woodfuel demand as an exogenous factor derived from a mix of national and sub-national studies supplemented by data from the Food and Agriculture Organization (FAO), International Energy Agency (IEA), and United Nations[1,25,26] (UN). Woodfuel demand has subsistence and commercial components. Subsistence demand occurs primarily in rural areas, where people collect their own fuel using simple non-motorized forms of transportation from within a few hours of their homes. Commercial demand originates in urban and some densely populated rural locations and is typically supplied by motorized transport over much longer distances.

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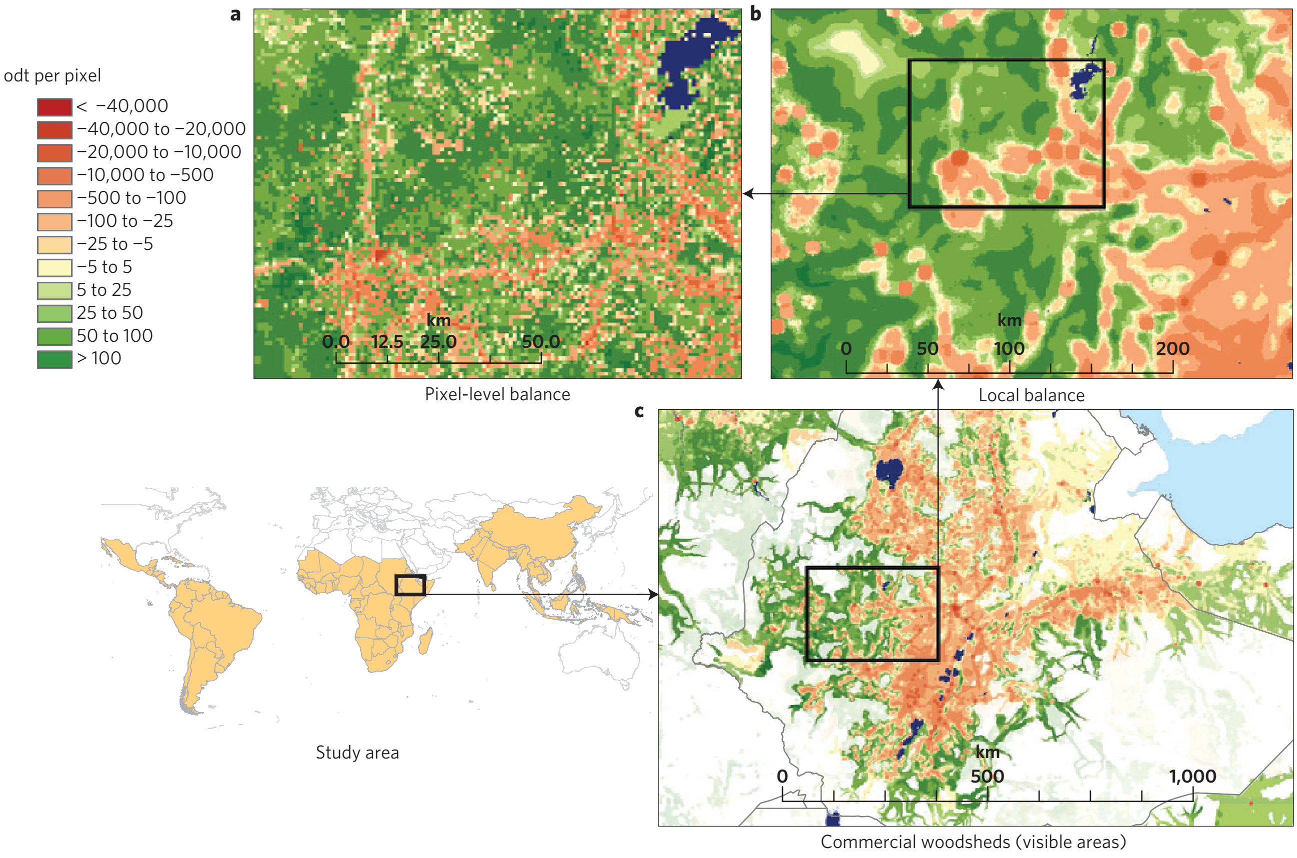

Figure 1 | Mapping of a high-deficit zone in East Africa. a, Pixel-level supply-demand balance. **b**, Local-level balance. **c**, Commercial balance. odt; oven-dry tonnes of woody biomass.

We develop a map of supply–demand balance by estimating harvesting pressure, first from subsistence and then commercial harvesters (Fig. 1a,b). Areas exploited to satisfy commercial demand form a 'woodshed', which represents the region that would satisfy demand if the full mean annual increment (MAI) is used[27] (Fig. 1c shows commercial woodsheds for a high-demand area of East Africa; Supplementary Fig. 5 shows the entire pan-tropics).

Woodfuels and LCC

Many woodfuel-dependent regions are characterized by high rates of deforestation. Others, particularly parts of China and India, have experienced recent afforestation. Although not directly linked to woodfuel demand, these processes, which we define collectively as LCC, impact woodfuel supplies. Deforestation creates large volumes of non-renewable woodfuel[28,29], and afforestation augments renewable woodfuel supplies by adding to the growing stock of 'dendro-energy biomass' (DEB). Neither process has been explicitly accounted for in previous woodfuel assessments. When deforestation occurs in regions accessible to woodfuel users, the cleared woody biomass may be used as timber and woodfuel. Similarly, afforestation adds DEB equivalent to the MAI of the surrounding land class. However, the degree to which LCC by-products are actually used as woodfuel is unknown. To accommodate this uncertainty, we explore two scenarios, described in Table 1. In Scenario A, we assume LCC by-products are not used. In Scenario B, we assume they are used, yielding two NRB components ($\mathrm{NRB}_{\mathrm{B1}}$ and $\mathrm{NRB}_{\mathrm{B2}}$): $\mathrm{NRB}_{\mathrm{B1}}$ indicates the use of LCC by-products; $\mathrm{NRB}_{\mathrm{B2}}$ indicates the wood harvested in excess of MAI to satisfy the demand that remains after accounting for the use of those by-products. In populated regions experiencing high rates of deforestation, large volumes of DEB are accessible, and $\mathrm{NRB}_{\mathrm{B2}}$ may be zero (Supplementary Section 5).

By combining woodshed mapping of commercial demand with localized supply–demand balances, we define the minimum quantity of NRB that would be required to meet existing demand (Supplementary Section 5). In this approach, we assume that woodfuel consumers manage their resources sustainably to the greatest extent possible so that unsustainable harvesting occurs only after the sustainable supply in a given location has been fully exploited. Thus, minimum NRB indicates the degree to which a given region can sustainably meet woodfuel demand under ideal management. However, ideal management is unlikely. To simulate suboptimal harvesting, we assume that harvesting sometimes exceeds sustainable levels in some areas even if the sustainable supply in an adjacent accessible area has not been fully exploited. To estimate the extent of this deviation, we use a proxy defined by the fraction of each country's forested area under formal management plans (Methods). From this we derive an 'expected' quantity of NRB, which we also express as a fraction of the total harvest (fNRB). Both minimum and expected NRB are expressed in absolute terms and as a fraction of the total harvest for a given region. We report expected NRB below; minimum NRB is given in Supplementary Information.

Woodfuel sustainability

Woodfuel demand in 2009 was $\sim$1.36 Gt. If by-products of LCC were not used (Scenario A), pan-tropical expected $\mathrm{fNRB}_{\mathrm{A}}$ was 27–30% (367–413 Mt). If by-products of LCC were used (Scenario B), we estimate they contributed 8.3% (113 Mt) of pan-tropical woodfuel supply ($\mathrm{fNRB}_{\mathrm{B1}}$). We also find that 22–25% (296–340 Mt) of the remaining demand was harvested

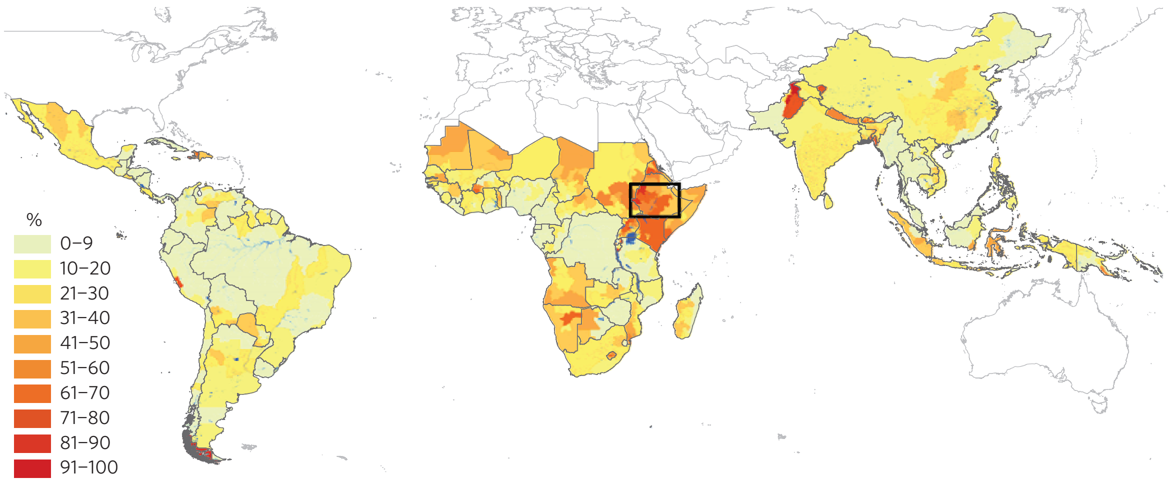

Figure 2 | Pan-tropical expected fNRB$_{B2}$. Shading indicates the percentage fNRB estimated in sub-national units resulting from direct woodfuel harvesting (Scenario B2). The rectangle shows the region illustrated in Fig. 1.

Table 1 | Different assumptions considering the use of LCC by-products.

	Assumption	Comment
A	LCC by-products generated in accessible regions are not used for woodfuel. Woodfuels are harvested entirely from other sources. NRB$_A$ is calculated as the quantity of non-renewable biomass from sources unrelated to LCC.	NRB$_A$ is applicable where LCC by-products are inaccessible to smallholders despite being physically proximate. This might be the case if large-scale farming or timber extraction drives LCC on private land that smallholders cannot enter.
B	LCC by-products generated in accessible regions are used as woodfuel. Two quantities are calculated: NRB$_{B1}$ refers to the amount of LCC by-products used to meet woodfuel demand in a given region. By-products of deforestation are always considered non-renewable and by-products of afforestation are considered renewable. NRB$_{B2}$ refers to the amount of woodfuel from other sources required to meet demand after LCC by-products are exhausted. LCC by-products may meet 100% of demand so that NRB$_{B2}$ = 0.	The sum of NRB$_{B1}$ and NRB$_{B2}$ indicates the total quantity of unsustainable woodfuel consumption that occurs when woodfuel users have access to LCC by-products. These values are applicable in regions where LCC is driven by smallholder agriculture or regions hosting intense commercial woodfuel extraction. Household energy interventions can mitigate NRB$_{B2}$, but it is unclear how they would affect NRB$_{B1}$.

unsustainably (fNRB$_{B2}$). Adding fNRB$_{B1}$ and fNRB$_{B2}$, the total fraction of NRB using LCC by-products is 30–34%. The uncertainty results from uncertain productivity and contribution of plantations (Supplementary Section 6). This is largest in Asia, where forest plantations may be a substantial source of supply, and smallest in sub-Saharan Africa, which has few plantations[30]. Figure 2 shows a global map of fNRB$_{B2}$ (maps of fNRB$_A$ and fNRB$_{B1+B2}$ are shown in Supplementary Fig. 7).

We define woodfuel 'hotspots' as regions in which expected fNRB exceeds 50%, that is, regions in which most harvested woodfuel is unsustainable. Hotspots encompass ~4% of pan-tropical areas and are inhabited by 6% of the pan-tropical population. The largest hotspot incorporates a swath of East Africa extending from Eritrea through western Ethiopia, Kenya, Uganda, Rwanda and Burundi. Expected fNRB$_{B2}$ exceeds 50% in 43 sub-national units throughout this region, encompassing 26% of the region's population. Additional hotspots also occur in western and southern Africa, but these do not cover large contiguous areas (Fig. 2). Notably, much of sub-Saharan Africa is characterized by fNRB$_{B2}$ below 20% including provinces of Angola, Cameroon, Central African Republic, Congo, DR Congo, Mali, Mozambique, Nigeria, South Africa, Tanzania, Zambia and Zimbabwe: home to 55% of sub-Saharan Africa's population.

In Asia, hotspots occur in parts of Pakistan, Nepal, Bhutan, Indonesia and Bangladesh. Expected fNRB$_{B2}$ in Pakistan is 79%, the highest national value in the entire sample. In two Pakistani divisions, fNRB$_{B2}$ exceeds 90%. Notably, Asia's woodfuel hotspots are distinct from areas of high deforestation. For example, deforestation rates in Indonesia, Malaysia, Cambodia and Laos are among the world's highest[31], largely as a result of agricultural expansion[16]. In contrast, China and India, the largest woodfuel-consuming nations, both experienced net afforestation in recent years[30]. At a national level fNRB$_{B2}$ is 10–22% in China and 23–24% in India. The wide range observed in China is a result of uncertainty in the productivity of plantation forestry, a potentially large source of China's woodfuel supply (Supplementary Fig. 6).

Latin America hosts the lowest traditional woodfuel consumption; Haiti is the only nation in which expected fNRB$_{B2}$ exceeds 50%. Still, fNRB$_{B2}$ exceeds 30% in many sub-national units including most of Dominican Republic and parts of Bolivia, Colombia, Ecuador, El Salvador, Mexico, Paraguay, Peru and Venezuela. As in Asia, high rates of deforestation are due primarily to agricultural expansion[16]. By-products of LCC in many parts of Belize, Brazil, Ecuador, Honduras, Mexico, Nicaragua, Panama, Peru and Venezuela are sufficient to meet most or all woodfuel demand (Supplementary Fig. 6).

Worldwide, over 275 million people live in woodfuel hotspots: nearly 60% in Asia, 34% in Africa, and the remaining 6% in Latin America. Figure 3 shows the regional distribution of population by fNRB$_{B2}$ decile.

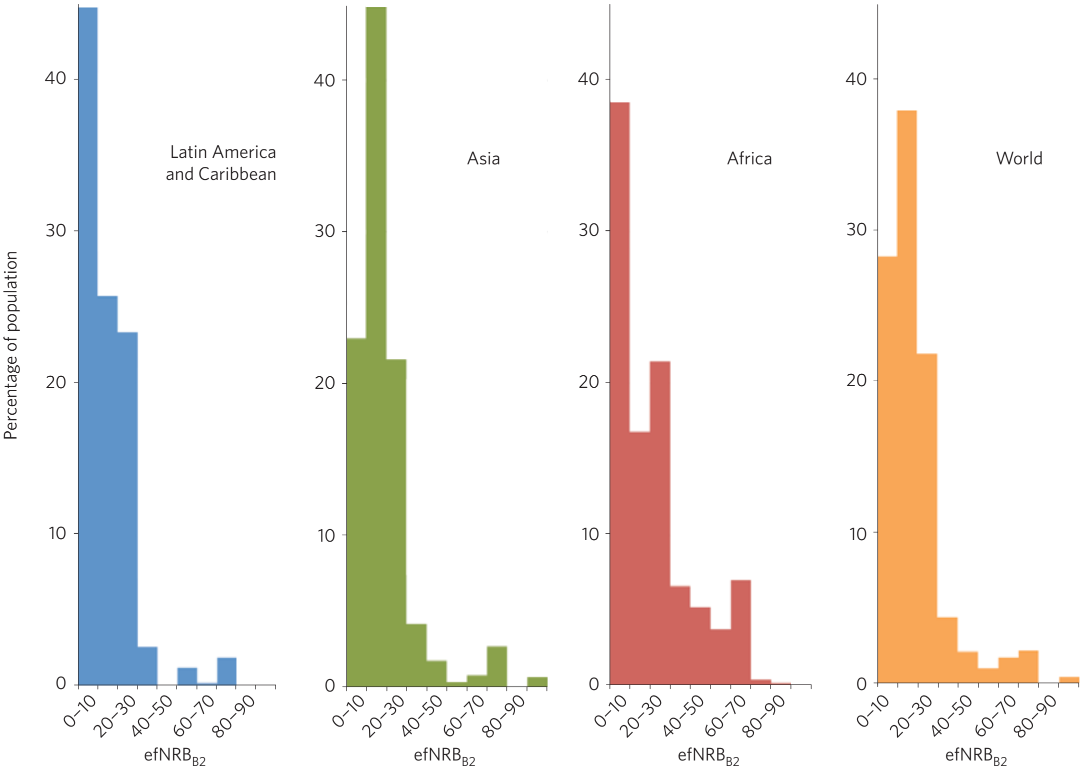

Figure 3 | Distribution of regional population by expected $fNRB_{B2}$ decile.

GHG emissions

Climate impacts arise from emissions of well-mixed GHGs, which include CO_2 and CH_4, and SLCFs, which include black and organic carbon aerosols, CO and volatile organic compounds (VOCs). Emissions of well-mixed GHGs and SLCFs as a result of unsustainable harvesting and incomplete combustion from traditional woodfuels (Methods) were 1.0–1.2 Gt of CO_2 equivalent (CO_2e) in 2009: 1.9–2.3% of global emissions and 3.5–4.3% of emissions in the pan-tropical region[32]. National emissions vary widely (Supplementary Table 2). India and China have the largest populations of traditional woodfuel users and highest overall emissions, but relatively low per capita emissions. In contrast, Kenya, Ethiopia and Uganda, which constitute part of the East African hotspot, rank among the highest emitters in absolute and per capita terms.

There is geographic variation in the mix of pollutants emitted by traditional woodfuels because of variations in fNRB and in the extent of charcoal use, which has different emission characteristics from fuelwood (Methods). Globally, after accounting for uptake by the fraction of woody biomass that is sustainably harvested, CO_2 contributes 34–45% of total climate forcing. Black carbon has a similar impact, contributing 35–42%, and CH_4, CO and VOCs account for the remaining 31–37%. This variation has policy implications; at present, carbon markets value reductions of CO_2, CH_4 and N_2O, but do not value black carbon abatement, which favours interventions in regions with high fNRB.

Mitigation potential of efficient cookstoves

Interventions in household energy have been implemented for decades with multiple objectives[33]: including forest conservation; health improvements; and climate change mitigation, as well as poverty alleviation and economic development. The Global Alliance for Clean Cookstoves (GACC), the largest stove programme so far, proposes to deploy 100 million improved stoves by 2020 (ref. 23). With large spatial variation in fNRB, impacts of interventions vary with geographic patterns of stove uptake. We examine this variation with four intervention scenarios (Methods and Supplementary Section 7).

We optimistically assume that 100 million state-of-the-art improved cookstoves are successfully disseminated according to different scenarios. Resulting emission reductions range from 98–161 $MtCO_2e\,yr^{-1}$. The largest reductions result from targeting the highest per capita woodfuel consumers. This is followed by reductions achieved by targeting consumers in regions with the highest rates of NRB, although uncertainties in emission reductions from individual stoves make the difference insignificant. The smallest reductions result from dissemination in the most business-friendly countries. The emission reductions achieved by prioritizing health improvements fall between these extremes (Fig. 4).

Discussion and implications

One limitation of the study is a lack of reliable woodfuel consumption data. When possible, we used national and sub-national data sets. However, for most countries, we relied on data compiled by international organizations containing unknown uncertainties that make it difficult to communicate the uncertainty in these results. A second limitation is that the analysis considers a single year and does not account for potential behavioural changes among woodfuel users in response to scarcity. Potential responses include decreasing consumption, switching to non-woody fuels, or taking measures to increase woody biomass supply. Such responses are site-specific and difficult to model globally, but they could be incorporated in national and sub-national dynamic models.

Using the best available data, we estimate that unsustainable harvesting and incomplete combustion contributed 1.9–2.3% of global emissions of well-mixed GHGs and SLCFs in 2009. Globally, emissions were split evenly between CO_2, black carbon and other SLCFs. In 12 nations, emissions from woodfuels were 50% or

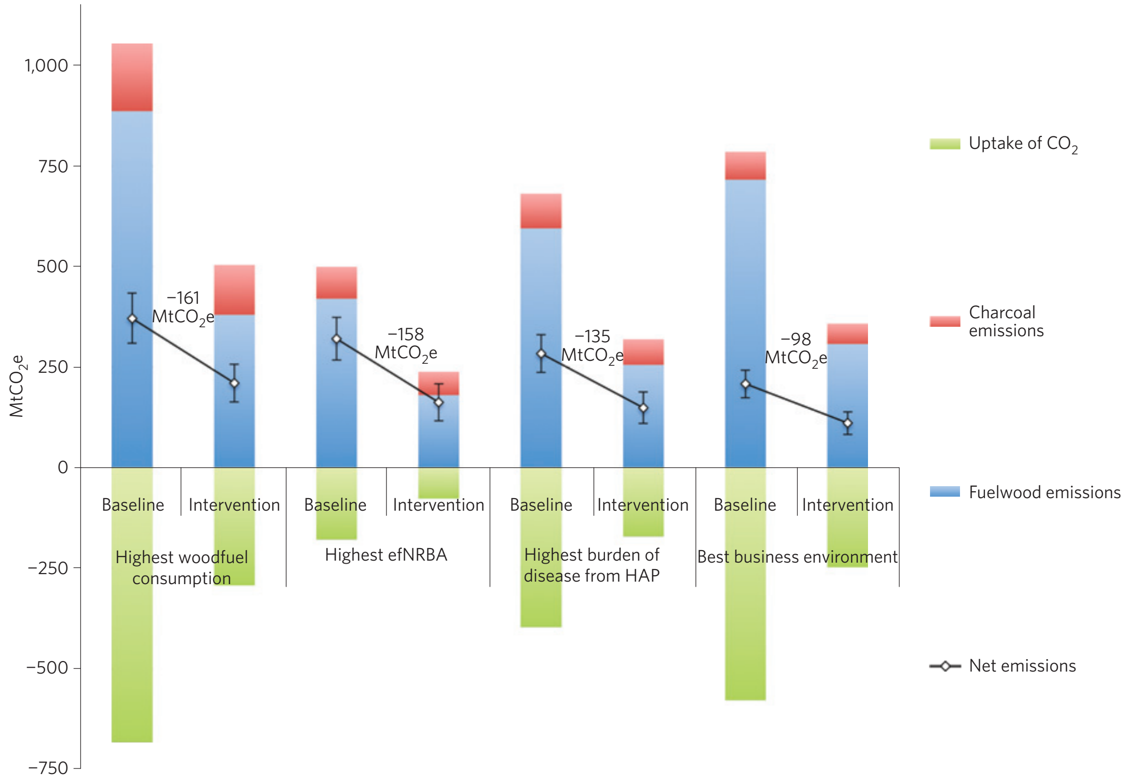

Figure 4 | Annual emissions and emission reductions resulting from fulfilling GACC's objective of 100 million stoves disseminated through interventions with different priorities. Bars indicate GHG emissions/uptake, data points show net emissions, error bars indicate standard deviations, and numbers indicate annual reductions achieved by shifting from baseline to intervention.

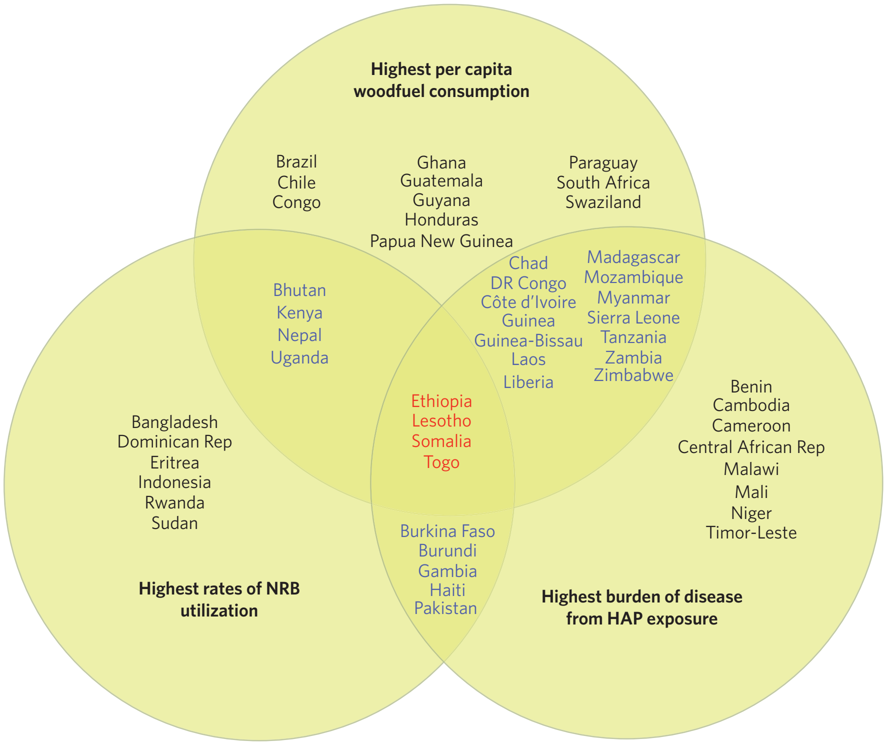

Figure 5 | Countries with highest per capita woodfuel demand, highest expected $fNRB_{B2}$, and highest burden of disease from HAP exposure.

more of the country's total emissions, demonstrating the dominant role that traditional woodfuels have in places with few industrial emissions (Supplementary Table 2).

Our estimates of fNRB are considerably lower than estimates used by woodfuel projects in the carbon market. Project revenues depend directly on fNRB. A review of 305 carbon projects in 45 countries reveals a median fNRB of 90% with minimal regional variation (Supplementary Section 6). We identified only four countries in which sub-national fNRB exceeds 80% as a result of woodfuel demand. Just 8% of existing projects fall within these areas. Thus, project developers are very likely overstating the emission reduction potential of improved stoves.

Household energy forms a major component of the United Nations' promotion of 'Sustainable Energy for All'[34]. However, high upfront costs are a barrier to implementing sustainable solutions. Despite finding lower fRNB values than market actors assume, successfully disseminating 100 million state-of-the-art cookstoves would reduce traditional woodfuel emissions by 98–161 $MtCO_2e\,yr^{-1}$. At US$11 per tCO_2e, the average price of offsets from stove projects in 2012 (ref. 35), these reductions would be valued at US$1.1–1.8 billion if black carbon can be integrated into carbon markets. This far exceeds current investments in household energy in the Global South, which do not garner the same level of finance as other major health impacts such as malaria, tuberculosis and HIV. In addition, we find that policy objectives are important determinants of emission reductions, introducing variation of 60%. Countries with high per capita woodfuel use or high NRB rates yield the largest emissions reductions. However, neither group overlaps completely with countries experiencing the highest disease burden from woodsmoke exposure (Fig. 5). Thus, improved stove dissemination among populations suffering from the largest disease burden results in fewer emission reductions than dissemination in regions with high rates of woodfuel consumption or unsustainable harvesting. However, we identified a small group of countries that rank poorly in all categories (red text in Fig. 5). Others rank poorly in two out of three categories (blue text in Fig. 5). These countries deserve clear prioritization. The sub-national data set generated by this research can be used to more accurately identify high-priority areas and pinpoint locations where interventions would have the greatest impact. Moreover, by identifying areas where woodfuel-driven degradation or deforestation is likely to occur, our assessment fills a critical gap in knowledge about the extent to which woodfuel demand may contribute deforestation or forest degradation and informs emerging REDD-based approaches to climate change mitigation.

Methods

We use the WISDOM model[36] (Supplementary Section 1) to characterize sustainability and net carbon emissions of traditional woodfuels in 90 developing countries located primarily in tropical regions, using 2009 as a base year. Woodfuel demand was derived from national and sub-national studies (Supplementary Section 1) supplemented by data from the FAO, IEA and UN (refs 1,25,26). From these data, we mapped subsistence and commercial components of traditional woodfuel demand. Subsistence demand occurs in rural areas, where people use woodfuels they collect themselves or purchase locally. This wood is harvested within a few hours' walking distance. Commercial demand originates in urban and some densely populated rural locations and is carried using motorized transport over longer distances (Supplementary Section 1).

Woodfuel supply is defined by the productivity of woody biomass, which we model as a function of above-ground biomass (AGB) stock. We use recent maps of land cover and ecological zones[37,38] to define a broad system of land units, including cropland and crop mosaic (often neglected in assessments of woodfuel supply). Each land unit is assigned an AGB stock using three types of source: AGB distribution maps; geo-referenced field plots; and forest inventories from known locations for specific forest types (Supplementary Section 1). AGB distribution was derived from two recent data sets[39,40]. To accommodate disagreements in the two data sets, we gathered data from hundreds of geo-referenced field plots and forest inventories. We subtract woody components not typically used for woodfuels (twigs, leaves and stumps), to build a map of DEB stock (Supplementary Fig. 2). We then estimate woodfuel supply as the MAI of DEB, which we model as a functional relationship between ~2,800 spatially explicit field observations of MAI and corresponding AGB (Supplementary Section 2).

We then make adjustments for potential supply from plantations[41,42] (Supplementary Section 3) and accessibility. Accessibility has legal and physical determinants. Legal accessibility is based on IUCN (International Union for Conservation of Nature) categorization of 'Protected Areas' (Supplementary Section 3). Physical accessibility is a function of the effort required to access woody biomass from a consumption site. We use an inverse function of friction in geographic space for subsistence and commercial demand (Supplementary Section 3) and map the distribution of accessible DEB (Supplementary Fig. 3 and Table 1).

LCC is accommodated by estimating the amount of DEB produced by deforestation and afforestation processes based on data from FAO (ref. 1) distributed spatially using data from Forest Monitoring for Action[43]. Biomass from large-scale deforestation in remote areas of the Amazon or Indonesian rainforests is often burned on site[44,45]. Only LCC occurring in areas that are accessible (as defined above) contributes to NRB. The actual quantity of LCC by-products used as fuel is unknown. Even in accessible areas, some materials may be burned *in situ* or left to decay. To accommodate this uncertainty, we explore two variants of LCC by-product utilization (Table 1 and Supplementary Fig. 5).

We combine the commercial and subsistence supply–demand maps to define the minimum quantity of NRB that would be required to meet existing demand (Supplementary Section 4). This assumes that unsustainable harvesting occurs only after the sustainable supply in a given location has been fully exploited. However, ideal management is unlikely. To simulate more realistic harvesting, we assume that harvesting exceeds sustainable levels in some areas even if the sustainable supply in an adjacent area has not been fully exploited. To estimate the extent of this deviation, we use a proxy defined by the fraction of each country's forested area under formal management plans[30] (Supplementary Section 5).

We then define local balance assuming subsistence users do not travel more than a few kilometres to access woodfuels[46,47] (Supplementary Section 4, Fig. 1a and Supplementary Fig. 4). Then we assess the commercial supply–demand balance in urban centres and rural regions with large deficits by defining a 'woodshed', which represents the region that a commercial demand centre needs to exploit to satisfy demand assuming that the full MAI is used[27]. We assume a threshold of 12-hour one-way travel. When several consumption sites are considered simultaneously, the woodshed is determined by the aggregate demand from all sites (Supplementary Section 4, Fig. 1b and Supplementary Fig. 5).

Annual GHG emissions from traditional woodfuels are estimated by accounting for two flows of GHGs. The first flow consists of combustion emissions including well-mixed GHGs (CO_2, CH_4 and N_2O) and SLCFs (black carbon, organic carbon, CO and VOCs). The second flow consists of CO_2 sequestered by the renewable fraction of harvested woodfuel. We use 100-yr global warming potentials to estimate climate impacts and we derive emissions from published analyses of woodfuel combustion and charcoal pyrolysis[48]. Sequestered CO_2 comes from results of this study (Supplementary Section 4).

To investigate the implications of GACC's 100 million-stove objective, we define scenarios representing broad goals of cookstove dissemination: climate change mitigation; decreasing dependence on NRB; reducing exposure to household air pollution (HAP); and economic development. Although these are stylized options, we chose these four scenarios to demonstrate that there are trade-offs between health and environmental policy objectives. We examine the outcome of focusing specifically on these objectives by targeting stove dissemination at the locations that rank among the highest in one of four categories described in Supplementary Section 6.

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Author contributions

R.D., R.B., A.G. and O.M. designed the study; R.D. conducted the pan-tropical WISDOM analysis and constructed the NRB model; R.B. calculated GHG emissions and emission reductions; R.D., R.B., A.G. and O.M. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.B.

Competing financial interests

The authors declare no competing financial interests.