Environmental Burden of Traditional Bioenergy Use

Omar R. Masera,1,* Rob Bailis,2 Rudi Drigo,3 Adrian Ghilardi,4 and Ilse Ruiz-Mercado1

1Institute for Ecosystems Research and Sustainability, 4Center for Environmental Geography Research, National Autonomous University of Mexico, Campus Morelia, Morelia 58190, Michoacán, Mexico; email: omasera@gmail.com, aghilardi@ciga.unam.mx, ilse.ruiz@cieco.unam.mx
2Yale School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut 06511; email: robert.bailis@yale.edu
3Independent consultant; email: rudi.drigo@tin.it

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Abstract
Approximately 40% of the global population relies on traditional bioenergy, accounting for 9% of global energy use and 55% of global wood harvest. However, knowledge about the environmental impacts of traditional bioenergy is fragmented. This review addresses several persistent questions and summarizes recent research on land cover change (LCC) and pollution emissions resulting from traditional bioenergy use. We also review recent studies analyzing transitions from traditional bioenergy to cleaner stoves and fuels.

Between 27 and 34% of the wood fuel harvest in 2009 was unsustainable, with large geographical variations. Almost 300 million rural people live in wood fuel “hotspots,” concentrated in South Asia and East Africa, creating risks of wood-fuel-driven degradation. Different fuels and stoves show variation in climate-forcing emissions. Many, but not all, nontraditional stoves result in lower emissions than traditional models. Traditional bioenergy makes substantial contributions to anthropogenic black carbon (BC) emissions (18–30%) and small contributions to total anthropogenic climate impacts (2–8%). Transitions from traditional fuels and devices have proven difficult. Stacking, i.e., the use of multiple devices and fuels to satisfy household energy needs, is common, showing the need to shift stove interventions from the common approach that promotes one fuel and one device to integrated approaches that incorporate deep understanding of local needs and practices, and multiple fuels and devices, while monitoring residual use of traditional technologies.
1. INTRODUCTION: EXTENT AND IMPACT OF TRADITIONAL BIOENERGY USE

The current extent and future evolution of traditional bioenergy use are closely related to several key challenges to sustainable development, ranging from local and global environmental concerns and health and gender issues to assuring universal access to clean energy.

By traditional bioenergy, we refer to wood fuels (firewood and charcoal), agriculture residues, and dung burned in open fires or rustic stoves used primarily for cooking, water heating, and space heating in developing countries. These stoves typically emit smoke directly into the indoor environment. Approximately 2.6 billion people worldwide, half the population in developing countries, burn solid biofuels [to meet basic energy needs (1)]. In addition, absolute numbers of traditional wood fuel users are expected to increase at least through 2030 (2, 3). Traditional bioenergy represents approximately 35% of global wood harvest (4) as well as an unknown fraction of crop waste, which collectively constitute 9–15% of global primary energy supply (5, 6). It is the main source of residential energy in many developing countries and dominates total energy supply in the least developed countries. Typical household wood fuel use varies from 2 to 6 ton/year with large regional variations (7). The end-use efficiencies of traditional devices are typically 10–20% (8), which is considerably lower than alternatives such as liquefied petroleum gas (LPG) (55%), electricity (70%), and some improved woodstoves (30–50%) (9–11).

Burning solid biomass in simple small-scale devices results in incomplete combustion, which emits health-damaging pollutants such as particulate matter (PM), carbon monoxide (CO), and others, contributing to high rates of morbidity and mortality. The World Health Organization

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1This review focuses on household use of wood fuels. Crop residues and dung are important in specific regions; however, no comprehensive global statistics exist. In addition, small cottage industries (e.g., brick-making, pottery, and bakery) are often important wood fuel consumers, but the data are too scarce to analyze global-scale impacts.
estimates that 3.9 million people worldwide die annually from exposure to household air pollution (HAP) (12). HAP is the leading environmental risk in the global burden of disease and the fourth leading risk factor overall. Women and small children are particularly vulnerable to HAP exposure, and it is a major contributor to illness and death among these groups in many poor countries.

In addition to the direct burden on health, traditional bioenergy users spend several hours per day collecting fuel or a considerable fraction of their income purchasing it (13, 14). Collectively, there is tremendous economic value embodied in traditional bioenergy. Commercial wood fuels are worth as much as US$37 billion/year, given, primarily, informal markets employing millions throughout developing countries. Self-collection of wood fuels utilizes as much as $37 billion in unpaid labor, accounting for ~7.5 billion person-days/year (Table 1).

In addition to severe health impacts, traditional bioenergy also results in multiple environmental impacts. Wood harvesting contributes to forest degradation or deforestation if wood is extracted faster than it can be regenerated. These processes of land cover change (LCC) impact local environmental conditions and emit CO2 (discussed further in Section 2). In addition, the incomplete combustion described above also releases climate-forcing agents (CFAs) (discussed in Section 3). Recent analyses estimate that traditional wood fuels, via unsustainable harvesting and incomplete combustion, contribute approximately 2% of global greenhouse gas (GHG) emissions including 20–30% of global black carbon (BC) aerosols (7, 15, 16).

Although the negative impacts associated with traditional bioenergy are profound, there are many barriers preventing adoption of more sustainable technologies. First, advantages of traditional fuels/stoves often go overlooked (17). For example, they are widely available and affordable, and have coevolved with cooking practices over many generations, making them integral components of multipurpose cooking systems (18) providing meals, hot water, food for livestock, space heating, and lighting. The smoke that damages health and contributes to climate change may assist with food preservation, help repel insects, and preserve roofing material. Although cleaner fuels and/or stoves might satisfy one or two of these needs, few provide such a wide range of services.

In addition, when desirable stove and fuel combinations are available, prevalent poverty across the Global South makes them difficult to access; and when LPG and electricity are available, people often use them for quick cooking tasks, but not longer fuel-intensive tasks, because the fuel is too expensive. LPG and electric stoves are also poorly suited to some local cooking practices. Hence, dividing cooking tasks among multiple stoves and fuels, which is referred to as stacking, is common. Stacking is not necessarily driven by economic factors: Taste, tradition, and social pressures are also important (discussed in Section 4) (19, 20).

The relationships between HAP and health outcomes are increasingly well characterized (12, 21–23). However, knowledge gaps persist in other key areas. Here, we review key topics related to the environmental burden of traditional bioenergy use, synthesizing findings from the past decade, highlighting knowledge gaps, and proposing plausible ways forward. Although researchers and development practitioners have been aware of the negative impacts of traditional bioenergy use for decades, until recently, limited resources have been directed toward research, development, and dissemination of solutions. Research on emissions from traditional bioenergy is progressing, but the results of recent studies show wide variability and substantial uncertainty about the magnitude of GHG emissions. We review these topics in Sections 2 and 3.

Also, spurred by growing interest in the co-benefits of reducing traditional bioenergy use, there is a growing literature on household energy interventions (24, 25). However, progress will be difficult without a better understanding of how transitions from traditional bioenergy actually progress within households. The interactions between social and technical factors are complex and remain poorly characterized. In Section 4, we review recent literature describing research on usage patterns of stoves and fuels. Section 5 closes with key lessons and recommended research priorities.
Table 1  Selected impacts of traditional bioenergy

| Issue                                           | Global impact                                                                 | DC impact                                                                                           | Source |
|------------------------------------------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|--------|
| People relying on solid biofuels               | 2.56 billion people in 2007; expected to reach 2.5–2.7 billion by 2030       | 52% of total population (22–100% of rural inhabitants, depending on the country); total population was 4.9 billion (2.8 billion rural and 2.1 billion urban in 2009) | 1      |
| Wood harvesting                                | 55% of global harvest (~1.87 billion m³ out of 3.4 billion in 2010)           | 79% (1.4 billion m³) of the total harvest in DC (90% in Africa, 66% in Asia, and 57% in Latin America) | 4, 70  |
| Forest degradation/deforestation               | linked to GHG emissions (see GHG emissions below)                             | 27–34% of the total wood fuel harvest in 2009 is nonrenewable; ~275 million rural people living in hotspots where fuelwood harvesting is nonrenewable | 7, 70  |
| Energy use                                     | 37 EJ/year out of 52 EJ/year of global bioenergy use and 454 EJ/year of global energy use (71% and 8% of total use, respectively) | 37 EJ/year out of 165 EJ/year in developing countries (38% of total use)                           | 5, 8   |
| Health impacts                                 | HAP accounts for 3.9 million premature deaths or 4.8% of the total GBD; it is the second cause of premature deaths from environmental factors after tobacco smoking (12% due to pneumonia, 32% stroke, 27% ischaemic heart disease, 21% COPD, and 8% lung cancer)a | ~98% of the disease burden caused by HAP occurs in DC                                             | 12     |
| GHG emissions                                  | 1.0–1.2 Gt CO₂e: 1.9–2.3% of global emissions, 49% of the warming due to black carbon, 32% of CO emissions from human sources, ~15% from ozone-forming chemicals, 4% from methane, and ~1% from net CO₂ emissions | 3.5–4.3% of total emissions in the pantropical region                                               | 7, 145 |
| Time/income                                    | global market of traditional wood fuels may reach US$37 billion/year and gives employment to several million people; another ~$37 billion is the value of unpaid labor for collecting fuelwood, which accounts for ~7.5 billion person-days/year | average time spent on fuelwood collection in Africa ranged from 0.3 to 4 h/cap/day; in Latin America wood collection times are also within this range, with typical values closer to 0.5–1 h/day | 14; see also authors' estimatesb |

Abbreviations: COPD, chronic obstructive pulmonary disease; DC, developing countries; GBD, global burden of disease; GHG, greenhouse gas; HAP, household air pollution.

aThe disease burden from HAP includes coal users, who reside primarily in China and other countries in northern Asia.

bWe assume that from the total wood harvested globally, 20% is sold at an average price of $70/t and that 80% is collected; charcoal is sold at an average price of $200/t. We estimate the typical collection time of a person-load of wood (30 kg) to be 2 h, or that 8 journeys are needed to collect 1 ton of wood. To assign a monetary value to unpaid labor for collecting fuelwood, we assume an average global shadow price of labor of $5/day (i.e., we assume that if paid, this labor would need to be hired at an equivalent wage of $5/day). Socioeconomic impacts also include reduction in the income opportunities, productivity, gender equity, and wellbeing that have been associated with the time, cost, and/or risks related to fuel collection and usage patterns.

2. UNDERSTANDING THE CONTRIBUTION OF TRADITIONAL WOOD FUELS TO DEFORESTATION AND FOREST DEGRADATION

The contribution of traditional bioenergy to LCC depends on the rate of extraction and productivity of woody biomass in the affected regions. Harvested areas include managed and unmanaged forests, woodlands, trees on farms, plantations, woodlots, and other communally managed resources, as well as roadsides and riparian buffer zones. If the rate of wood harvest exceeds productivity over an extended time period, the stock of woody biomass declines, creating an unsustainable
situation and leading to degradation or deforestation. Stocks lost in a given time period are considered nonrenewable biomass (NRB) (see Supplemental Material Section 1; follow the Supplemental Material link from the Annual Reviews home page at http://www.annualreviews.org).

Estimating NRB requires knowledge of both demand (the quantity extracted) and sustainable supply (the mean annual increment or MAI) of woody biomass. Analyses of NRB typically use global or national statistics to determine demand. However, as the majority of traditional bioenergy is self-collected or procured through informal markets, accurate data are difficult to obtain. In addition, harvesting depends on locally specific legal and biophysical factors and may be moderated by competing sources of demand (26). Supply is also site-specific, depending on land cover and ecological conditions.

Moreover, other drivers of LCC can confound NRB analyses. For example, many places where traditional bioenergy is common are characterized by high rates of LCC driven by factors unrelated to energy (27). If LCC occurs in areas that are accessible to traditional bioenergy users, it can serve as a source of (unsustainable) supply, supplementing extraction specifically to meet wood fuel demand (see Supplemental Material Section 2).

2.1. Studies of Wood Fuel Supply and Demand

Interest in bioenergy-driven LCC dates to the 1970s, when concerns about wood fuel scarcity, the “other energy crisis,” were first raised (28). One early analysis predicted pervasive deforestation by the year 2000 due to a widening gap between wood demand and supply (29). However, crises predicted by this and other studies released at the time (30, 31) never materialized. Later analyses stressed that traditional bioenergy demand alone was likely not a major deforestation driver, except in cases of intense commercial activity (32–34).

There is now some consensus that traditional bioenergy demand does not drive deforestation, but several studies argue that it contributes to degradation, leading to reductions in biomass stock and productivity or changing species composition. However, the role of wood fuel demand relative to other drivers of degradation is unclear. Hosonuma et al. (27) argue that demand for timber is a more important driver of forest degradation in Asia and Latin America, whereas wood fuel demand drives most degradation in Africa. Recent assessments of traditional bioenergy sustainability conducted in different parts of the Global South find conflicting results (27, 36–39), suggesting that geography and spatial scale are important.

Here, we review peer-reviewed papers published since the early 1990s that model the relationships between traditional bioenergy supply and demand. Models vary in their use of spatial and temporal dynamics, as well as the scale of analysis, which varies from individual communities to near global in extent. Analyses of large geographic regions permit consistent comparisons of broad areas and help identify priority zones for interventions. However, much of the data and assumptions cannot be validated, making the results ambiguous and expressible only as broad ranges of biomass surplus or deficit. In contrast, landscape- or project-level analyses are easier to validate, leading to more reliable results.

Local relationships such as de facto and de jure rights of access to biomass resources affect landscape-level supply and demand. Their local character prevents the integration of these

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2The Food and Agriculture Organization of the United Nations defines deforestation as “[t]he conversion of forest to other land use or the permanent reduction of the tree canopy cover below the minimum 10% threshold,” and forest degradation as “the reduction of the capacity of a forest to provide goods and services” (35, p. 35).
factors into macroscale analyses, but they can be incorporated into microscale models. However, microstudies lack generalizability. National-level approaches present a compromise, permitting the integration of subnational relationships and policies and producing results that are relevant to the entire country. They also permit higher spatial resolution than global studies and allow the incorporation of new information, such as survey data or land use/cover maps, which can be incorporated more easily. Lastly, national-level analyses are easier to validate with ground data and can be helpful in planning localized interventions.

Time also plays an important role in modeling traditional bioenergy. Both supply and demand are time dependent. After biomass is harvested, the landscape responds with new growth. In addition, consumer behavior has a temporal component; harvesting patterns may be seasonal and behavior may change when resources become scarce. Moreover, time plays a functional role in modeling traditional bioenergy.

We classify the analyses in three groups based on their use of spatial and temporal parameters:

1. **temporal, nonspatial**: models that evolve in time based on previous states of the system, rather than static parameters, but lack geo-processing operations;
2. **spatial, nontemporal**: studies that apply geoprocessing operations such as proximity, overlay, or cumulative cost, i.e., beyond maps of administrative units depicting data from a table, but lacking any temporal dynamics;
3. **spatiotemporal**: studies that incorporate both spatial dynamics and geoprocessing.

### 2.1.1. Temporal, nonspatial

Several dynamic models have been developed to evaluate inter-related effects of LCC drivers (40–45). This approach captures relationships between demand for resources in economic terms and biophysical response of surrounding woodlands. The results show how demographic pressure intensifies the impact that demand for traditional bioenergy has on degradation. For example, Hofstad (44) projected that increasing charcoal demand in Tanzania would cause higher prices and larger harvested areas. He noted, “the exploited area forms a wedge, which expands inland as net price of charcoal increases” (44, p. 17). This resembles observations from Ahrends et al. (38), who identified “waves of deforestation” driven by charcoal producers following high-value timber operations outside Dar es Salaam. A related study (41) modeled land clearing, grazing, and wood extraction to forecast forest degradation in rural Senegal. This analysis found that increasing demographic pressure worsens degradation. However, increased wages for charcoal producers and lower charcoal prices slow degradation, as charcoal production becomes less attractive. Using a similar approach, Namaalwa et al. (45) simulate charcoal supplies for Kampala, predicting acute wood scarcity, and model deforestation and forest degradation in woodlands near two Ugandan villages, accounting for fuelwood collection and charcoal production (40).

Alam et al. (46) simulated the impact of traditional bioenergy demand in Bangladesh between 1981 and 2000, concluding that increasing demand drives deforestation in all scenarios. Hartter & Boston (42) modeled caloric requirements for analyzing fuelwood and agricultural land required for meeting individual energy needs. After simulating a Ugandan village, they conclude that caloric demand is an important driver of fuelwood consumption leading to deforestation. Other temporal nonspatial models examine changes in woodland structure and composition. For example, Rüger et al. (47) simulate changes in tropical montane forests and find structural changes may last decades or centuries, affecting fuelwood quality.

### 2.1.2. Spatial, nontemporal

Adding a spatial component allows features such as transportation infrastructure and land cover categories to be explicitly modeled. Several models have been developed to analyze wood fuel sustainability. In these analyses, geoprocessing operations integrate
maps of demand and supply to quantify supply deficits and identify areas that may experience wood fuel-driven LCC (48–57; see also http://www.wisdomprojects.net/global/index.asp). The Woodfuel Integrated Supply Demand Overview Mapping (WISDOM) model exemplifies this approach (48, 58; http://www.wisdomprojects.net/global/index.asp). To date, more than two dozen national and regional WISDOM case studies in Africa, Asia, Latin America, and Europe have been completed, as well as a pantropical assessment, which we describe in more detail in Section 2.2. Applied mostly at the national level, WISDOM has provided support to sustainable wood energy planning and REDD+ mechanisms in several countries. The WISDOM case studies have helped develop local capacities, providing country-level coherent mapping and integration of data related to wood fuel resources, identifying critical areas for wood fuel supply and demand interventions, understanding the implications of alternative future scenarios on wood fuel use, and helping formulate more adequate policies regarding traditional wood fuel use (http://www.wisdomprojects.net/global/index.asp).

2.1.3. Spatiotemporal. Spatiotemporal models integrate time-dependent and spatially explicit data. Some studies analyze the impact of wood fuel extraction on habitat degradation and biodiversity loss in ecologically sensitive areas. One set of studies has focused on the Wolong Natural Reserve in southwestern China (59–63). Using life histories and demographic data, researchers model size and spatial distribution of wood fuel demand and its impact on panda habitats. Impacts are expressed as habitat loss or gain, which facilitates empirical validation of model results through the comparison of simulations to land cover classifications from satellite images. This set of studies provides a framework for describing complex human–environment interactions characterized by nonlinearities and thresholds.

Cantarello et al. (64) also model impacts on a protected area. Using a spatiotemporal model, they find traditional bioenergy extraction targets high-value species. Christensen et al. (65) use an agent-based model to evaluate impacts on biodiversity. They explore policies based on collection quotas and protected areas to balance conservation and fuelwood demand. Others model the impact of demand reduction measures such as fuel-efficient stoves or fuel switching on LCC (66–69). Ghilardi et al. (66) model spatiotemporal response of aboveground biomass in business-as-usual and intervention scenarios and find reduced fuelwood demand lowers impacts on LCC. Salerno et al. (69) use a participatory modeling approach, in which multiple stakeholders contribute to the model by providing location and volumes of wood extraction, among other factors.

2.2. Pantropical Wood Fuel Demand, Supply Potential, and Balance

A recent pantropical assessment of traditional bioenergy, based on the WISDOM model, provides a coherent framework for examining the impact of traditional bioenergy consumption in 90 developing countries (see Supplementary Material Section 3 and References 7 and 70). Using 2009 as a base year, the study estimates that wood fuel demand was approximately 1.4 Gt/year (dry wood equivalent).

The assessment defines sustainable supply as the MAI of accessible aboveground woody biomass, excluding twigs and stumps, which are not typically used as fuel. Accessibility includes legal and physical factors. The potential pantropical supply of wood fuel is 3.6–4.0 Gt/year (a map of sustainable supply is shown in Supplemental Material Section 3). Figure 1 shows the localized supply/demand balance and identifies major deficit sites. A deficit arises if local demand exceeds supply. Commercial suppliers will likely meet demand in these areas by exploiting more distant resources. Total extraction at each location is the sum of local and commercial demand. In spite
of a surplus at a pantropical scale, harvesting may be unsustainable because many surplus areas are inaccessible to people in deficit locations. In addition, even in areas with accessible surpluses, harvesters may not manage resources optimally, such that some resources are overharvested whereas adjacent resources are not exploited at all (see Supplemental Material Section 3).

Many wood-fuel-dependent regions suffer high rates of deforestation. Others, particularly China and India, experience afforestation. Multiple factors drive these LCC processes (27). If LCC occurs in accessible areas, it generates woody biomass that may be used as fuel (71–73). Drigo et al. (70) account for uncertainty in the use of LCC by-products by examining two scenarios: One assumes LCC by-products are not used for energy and all wood fuel is obtained from direct harvesting (Scenario A); the second assumes accessible LCC by-products are used to satisfy wood fuel demand and, after the by-products are exhausted, people directly harvest wood fuels from available resources (Scenario B; see Supplemental Material Section 4).

The assessment expressed NRB as a fraction of total wood fuel harvest (fNRB; see Table 2). If by-products of LCC were not utilized, pantropical fNRB was 27–31%; if they were, then fNRB increased to 31–34%. LCC by-products constituted 8.5%, and direct wood fuel extraction constituted 22–25%. Figure 2 shows a map of NRB from direct wood fuel harvesting after accessible LCC by-products are utilized. NRB is expressed in relative (top) and absolute (bottom) terms (see Supplemental Material Section 4 for a map of Scenario A). These maps reveal a series of hotspots, defined as regions where 50% or more of direct harvesting is unsustainable. In East Africa, nearly 19% of the region and 26% of the population live in regions where NRB exceeds 50%. Elsewhere in Africa, hotspots are sparse; however, fNRB values between 20 and 50% are prevalent, covering 55% of the region and affecting 27% of the population.

Hotspots are prevalent in parts of South Asia, specifically Pakistan, Nepal, Bhutan, and Bangladesh. Notably, Asia’s wood fuel hotspots are distinct from areas of high deforestation. For example, deforestation rates in Indonesia, Malaysia, Cambodia, and Laos are among the world’s highest (74). LCC by-products are sufficient to meet the majority of wood fuel demand in many parts of the region. China and India, the largest wood fuel-consuming nations, both experienced net afforestation between 2000 and 2010 (75), and fNRB was relatively low, with 10–22% in China and 23–24% in India.

In Latin America, traditional bioenergy consumption is lower than in Asia and Africa and there are few hotspots. Only Haiti has an fNRB exceeding 50%. However, there are areas where fNRB exceeds 20% (Figure 2). As in Asia, high rates of deforestation are due primarily to agricultural expansion (27), and LCC by-products satisfy wood fuel demand in many regions.

In total, almost 300 million rural people live in hotspots, and 809 million rural people live in areas where fNRB values fall between 20 and 50% (Table 2). By depleting stocks of biomass in these regions, traditional bioenergy demand contributes to LCC.

2.3. Applications of Nonrenewable Biomass Estimations

Estimations of fNRB are utilized for quantifying the CO₂ emission reductions resulting from interventions such as improved stove or fuel switching programs that decrease traditional bioenergy consumption. Many interventions seeking to reduce traditional bioenergy consumption rely on carbon markets to generate revenue, which depends directly on fNRB. For example, as of June 2014, 287 projects in 47 countries were being implemented to generate carbon credits by reducing traditional bioenergy use. The median fNRB used to estimate the emission reductions achieved by these projects was 89% with minimal regional variation (see the supplementary information in Ref. 7). Results of the pantropical study were 60–70% lower, with very few subnational units
Major deficit sites
(Cumulative deficit within 20-km radius)
Zonal deficit = 0.4 Mt
Zonal deficit = 1.4 Mt
Zonal deficit ≥ 2.4 Mt

Figure 1
Local wood fuel supply/demand balance and location of major deficit sites. Data shown in oven-dry tons of woody biomass per pixel per year (od t year$^{-1}$). Pixel size 30 arc-second (0.86 km$^2$ at 0 Lat; 0.74 km$^2$ at ±30 Lat). Abbreviation: od t, oven-dry ton.
### Table 2: Regional Summary of Expected Annual NRB Extraction

| Region               | Harvest\(^a\) (Mt/year) | Scenario A: NRB values assuming accessible LCC by-products are not used for fuel (%) | Scenario B: NRB values assuming accessible LCC by-products are used for fuel\(^b\) | Total Mln (% | Rural Mln (%) | Total Mln (% | Rural Mln (%) |
|----------------------|--------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|---------------|---------------|---------------|---------------|
| Africa               | 443                      | 34.8–35.7                                                                        | 15.0                                                                             | 25.9–26.7     | 40.9–41.6     | 277 (33)      | 170 (32)      |
|                      |                          |                                                                                  |                                                                                  |               |               | 95 (11)       | 82 (15)       |
| Americas             | 189                      | 20.8–23.7                                                                        | 15.8                                                                             | 12.2–13.0     | 28.1–30.9     | 150 (26)      | 37 (29)       |
|                      |                          |                                                                                  |                                                                                  |               |               | 19 (3)        | 5 (4)         |
| Asia (and Oceania)   | 729                      | 24.2–29.2                                                                        | 2.7–2.9                                                                          | 22.0–26.7     | 24.7–29.6     | 969 (28)      | 602 (28)      |
|                      |                          |                                                                                  |                                                                                  |               |               | 161 (5)       | 109 (5)       |
| Pantropical          | 1,361                    | 27.2–30.5                                                                        | 8.5–8.6                                                                          | 21.9–25.1     | 30.5–33.7     | 1,396 (28)    | 809 (28)      |
|                      |                          |                                                                                  |                                                                                  |               |               | 275 (6)       | 197 (7)       |

Abbreviations: fNRB, fraction of total wood fuel harvest; LCC, land cover change; NRB, nonrenewable biomass.

\(^a\)Harvest includes woody biomass used as fuelwood, charcoal, and construction materials.

\(^b\)Scenario B consists of two components: NRB relative to the LCC by-products used as wood fuels (B1) and the component relative to the additional direct harvesting necessary to meet the residual demand (B2). Both are expressed as percent of total harvesting.
characterized by fNRB exceeding 80%. Bailis et al. (7) conclude that these projects are probably overestimating their emission reduction potential.

3. ASSESSMENTS OF EMISSIONS FROM TRADITIONAL BIOENERGY

Measuring emissions of CFAs from traditional bioenergy combustion has evolved in close parallel with research on emissions of HAP from traditional wood fuels (10, 76) and reflects a growing interest in co-benefits of climate change mitigation (77). Although impacts on climate change and public health are quite distinct, both are linked to processes of incomplete combustion inherent to small-scale cooking fires and both can be reduced through the adoption of cleaner stoves and/or fuels.

If biomass were fully combusted, only CO₂ and water vapor would be released. There would be no impact on health, and the climate impact would be limited to net flux of CO₂ to the atmosphere that occurs if wood is harvested unsustainably (Section 2). However, with incomplete combustion, hundreds of pollutants are emitted (78). Some, such as CO, volatile organic compounds (VOCs), nitrogen oxides (NOₓ), and particulate matter, impact both health and climate. Others, such as methane (CH₄), do not impact health but affect climate.

3.1. Characterizing Recent Studies of Cookstove Emissions

The bulk of empirical research on pollution from traditional bioenergy can be divided into studies quantifying emissions and studies quantifying concentrations and exposures. The link between indoor concentrations of harmful pollutants and health impacts of traditional wood fuels has been the subject of several recent reviews (12, 21–23). Here, we focus on climate impacts.

We review 36 studies reporting emission measurements from 117 different types of stoves using 297 different stove-fuel combinations published between January 2009 and August 2014 (see the Supplemental Material Section 6 for search criteria and descriptions of the papers described here). The studies include laboratory and field measurements of biomass fuels including wood and wood pellets, charcoal, crop residues, and dung. The stoves range from three-stone fires and other types of traditional stoves to mass-produced rocket-style and forced draft stoves, as well as experimental models that have not been disseminated in appreciable numbers. Some studies use a single stove to test different combustion conditions or fuels (79–82), whereas others use standardized fuels to test several stoves (83–85).

Since the initial work on co-benefits (10, 76), the focus of emission measurements has broadened to include more field-based studies to capture emissions in actual conditions of use, although laboratory measurements are still more common. Studies are geographically diverse, with laboratory-based studies occurring in China and several South Asian countries, as well as North and Central America. Field studies are less diverse, taking place in just three countries: China (86–90), Honduras (91), and Mexico (92). No published studies have taken place in Africa, although African stoves have been measured in North American labs (83–85, 93).

3.2. Pollutants

The pollutants measured reflect the growing importance of short-lived climate forcers. Early studies focused on well-mixed gases such as CO₂, CO, and CH₄ as well as PM. More recent studies disaggregate PM into black, elemental, and organic carbon (BC, EC, and OC, respectively) aerosols. Several studies also measure chemical and optical properties, as well as aerosol size distributions (79, 80, 87, 90, 93–96).

The studies report emission factors (EFs) of 33 individual pollutants or pollutant groups from 297 distinct stove-fuel combinations. Some measure EFs using different starting temperatures,
**fNRB**

(% of total direct harvesting)

- 0–10
- 11–20
- 21–30
- 31–40
- 41–60
- > 60%

**NRB**

of direct harvesting

(od t km⁻² year⁻¹)

- 0.0–1
- 1.1–2.8
- 2.9–5.2
- 5.3–8.0
- 8.1–12
- 13–15
- 16–20
- 21–27
- 28–50
- > 50
power outputs, or fuel moisture. CO and PM are the most common pollutants measured, reflecting a focus on health impacts. Studies reporting EFs for BC and OC are also well represented, while fewer studies report EFs for CO₂, CH₄, and VOCs (see Supplemental Material Section 6 for details).

Several earlier studies demonstrated that emissions in real conditions differ from laboratory-based emissions (97–99). Laboratory studies typically rely on variations of the water boiling test. They burn homogeneous, well-dried fuel and follow rigid procedures that do not reflect actual cooking practices, highlighting the need for more field measurements. However, field-based measurements are costly, logistically difficult, and place a burden on participating households. Thus, despite known discrepancies between measurements carried out in laboratory and field conditions, just eight of the 36 studies in this cohort were field-based (86, 87, 91, 92, 100–102).

Two studies directly compared field measurements to laboratory measurements as an integral part of the analysis (91, 92), and two others compared field results to lab-based EFs measured by others (87, 102). In addition, eight studies in the cohort, all from a single research group, were conducted in simulated kitchens (79–81, 88, 100, 103–105). These studies may come closer to actual cooking than laboratory measurements, but there are still differences between controlled conditions and real cooking; as such, we group them with lab-based measurements.

### 3.3. Results of Traditional Bioenergy Emissions Measurements

To analyze the results, we grouped stoves into eight broad categories. We examine EFs for individual pollutants, draw comparisons between stove/fuel categories, and consider relationships between pollutants. The stove categories include the following:

1. traditional stoves (T): three-stone fires, mud stoves, tripods, and unspecified others;
2. rocket stoves (R): Chulika, Envirofit, StoveTec, and unspecified others;
3. gasifier stoves (G): Belonio, Sampada, StoveTec TLUD, and unspecified others;
4. forced draft stoves (F): Philips fan, Oorja, Jinqilin, and unspecified others;
5. charcoal stoves (C): Geres, various Kenyan Jikos, Gyapa, Uhai, and StoveTec;
6. pellet stoves (P): various models of Chinese pellet stoves;
7. other nontraditional stoves (O): Vita, Philips, Berkeley Darfur, Patsari, Onil, Upesi, and Mayon;
8. not applicable (NA): specially designed burners used for EF measurements.

There is variability in emissions within and between stove types (see Supplemental Material Section 6 for details). In addition, improved stove categories result in lower emissions for some but not all forms of pollution. One reason for this is that EFs are presented with respect to fuel mass, which fails to account for differences in energy efficiency. Nontraditional stoves are usually more efficient than traditional stoves, particularly in laboratory settings. A comparison of EFs on an energy basis would show them in a better light; however, only six papers in this cohort report EFs in terms of energy delivered (82, 83, 88, 90, 96, 106). Most of the remaining studies lacked sufficient information to convert from mass- to energy-based EFs. Thus, EFs are analyzed with respect to fuel mass, which may bias results in favor of traditional stoves.

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**Figure 2**

Expected unsustainable fraction of direct wood fuel harvesting according to Scenario B2, expressed as percent of total annual harvesting (a) and as od t NRB/km² (b). Abbreviations: fNRB, nonrenewable biomass fraction; NRB, nonrenewable biomass; od t, oven-dry ton.
Most categories of nontraditional stoves have similar CO₂ emissions as traditional stoves. Only pellet stoves (P) are significantly higher, which indicates better combustion efficiency. CO₂ EFs from Gasifiers (G) and the NA category, which consists of EFs from two South Asian studies that used laboratory combustors to burn biomass (94, 107), are significantly lower than traditional stoves.

EFs for health-damaging pollutants such as CO and PM are significantly lower for most nontraditional stove categories. EFs for CH₄, derived largely from a single laboratory study (83), show little variation. Measurements of EFs for BC are mixed: Fan, gasifier, and pellet stoves have lower EFs than the traditional category; rocket stoves and other nontraditional models show higher EFs, although differences are only significant for rockets. OC EFs are similar. NOₓ EFs were reported by just two studies (101, 107). Variation in the data was relatively large, but differences between traditional and nontraditional stove categories were significant.

Published EFs also illustrate the extent to which emissions from charcoal differs from unprocessed biomass. With carbon contents 40–60% greater than wood or crop residues, charcoal emits significantly higher CO₂, CO, CH₄, and VOCs than other biomass fuels. HAP and CFAs are coemitted as a result of incomplete combustion. Although specific EFs vary, some pollutants are correlated. Figure 3a shows scatterplots of CO and PM; Figure 3b, PM₂.₅; Figure 3c, BC; and Figure 3d, OC, for various stove-fuel combinations. Traditional and nontraditional stoves are fit to a single regression line, and charcoal stoves (PM₂.₅ only) are fit to a separate line. There is a strong correlation in EFs from both traditional and nontraditional stoves with PM (R² = 0.82). Linear correlations between CO and PM₂.₅ BC and OC are somewhat weaker. These correlations are useful in health studies because CO emissions are easier to measure than PM. As a result, CO has been used as an indicator of exposure to biomass smoke, and significant exposure-response relationships have been measured between CO and respiratory infection (111, 112).

3.4. Comparisons of Lab-Based and Field-Based Measurements

Earlier studies have shown that stove emissions differ depending on whether measured in controlled or uncontrolled field settings (97, 99). By comparing EFs between and within studies, we find EFs measured by this cohort support these findings. However, direct comparisons are only possible for a few stove-fuel combinations. Figure 4 shows individual studies reporting EFs from controlled settings (the laboratory or simulated kitchens) and uncontrolled settings (real kitchens), using the same stove categories defined in Section 3.3. Data show significant differences (p < 0.05) in emissions between controlled and uncontrolled settings for CO₂ and CO from traditional and nontraditional stoves, as well as CH₄ emissions from nontraditional stoves. Differences imply that traditional stoves are less polluting in actual use (higher levels of CO₂ and lower CO), whereas the opposite may be true for nontraditional stoves (lower CO₂ and higher CO and CH₄). EFs for PM, BC, and OC from rocket-style stoves support this conclusion to some extent. However, these

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3With the exception of charcoal, biomass fuels included in these studies have a carbon content between 45 and 50%, which places an upper bound on CO₂ emissions per mass of fuel of roughly 1,800 g/kg. Charcoal consists of 70–80% carbon and emits 2–3,000 g of CO₂ per kg.

4Charcoal also has substantial upstream emissions, which increase charcoal’s total impact relative to other biomass (108–110).

5Two outliers were dropped from the CO-PM₂.₅ plot. These were data points from a gasifier stove burning rice husks (reported in 83) that differed in emissions characteristics from the other data in the graph.
Figure 3
Plots showing relationship and regression lines of EF data for (a) CO PM, (b) PM smaller than 2.5 μm in diameter (PM$_{2.5}$), (c) BC, and (d) OC. The PM$_{2.5}$ plot shows data for charcoal in red squares with a separate regression line. Error bars show standard errors. Abbreviations: BC, black carbon; CO, carbon monoxide; EF, emission factor; OC, organic carbon; PM, particulate matter.

comparisons are based on different studies utilizing different instrumentation and methodologies. Therefore, we caution against drawing conclusions from this evidence alone.

A preferable approach compares EFs in controlled and uncontrolled settings in the same study using similar instruments and protocols. However, only two studies in this cohort do this (91, 92). A third study compares field EFs to laboratory measurements of similar stoves (87), which is similar to the data we present in Figure 4.

Results of direct lab-field comparisons are mixed. One study, conducted on traditional and improved stoves in Mexico (92), measured CO and CO$_2$ emissions at different power outputs and used the ratio of CO$_2$/(CO$_2$ + CO) to define a simple proxy for combustion efficiency. In contrast to the data presented in Figure 4, the authors found traditional stoves had lower combustion efficiency in field settings than in the lab, with lower CO$_2$ and higher CO emissions at all but the lowest power output. Improved stoves demonstrated different behavior; at low power, CO emissions in field conditions were higher than in laboratory conditions. However, at medium and high power, the emissions in field conditions were lower than in the lab. On the basis of these results, those authors argue that lab-based stove testing should be modified to more closely mirror daily cooking, across a range of power outputs, to better reflect conditions of actual use.
The other study directly comparing lab and field-based emissions conducted emissions measurements over several years (91). Lab measurements were done in the United States and field measurements in Honduras using a mix of traditional and nontraditional stoves. The authors measured CO, PM, BC, OC, and aerosol optical properties. The authors found that PM emissions in field conditions were significantly higher than emissions measured during simulated lab cooking. Field conditions also showed greater variability. They conclude that results from lab testing should not be considered representative of real-world emissions. They recommend field tests be used to identify the factors that drive emissions and lab tests be designed to incorporate these factors.

### 3.5. Global Impacts of Wood Fuel Emissions

Several analyses have estimated global CFA emissions from traditional wood fuels in absolute terms and in relation to other anthropogenic emissions (Table 3). Estimates of CFA emissions vary widely as a result of different emission inventories and/or EFs, as well as varying assumptions about the sustainability of harvested wood, which affects net CO₂ (Section 2). Unger et al. (16) used an emission inventory for the year 2000 (113) and assumed that 10% of wood fuel was harvested unsustainably. Bond and colleagues (15) used observed values of direct radiative forcing from BC between 2000 and 2009 to scale-up emissions of climate forcers based on a different emissions inventory (114) and made no allowance for woody biomass regrowth. Bailis et al. (7)
Table 3 Global emissions from wood fuels reported in recent studies (Mt/year)

| Authors              | Base year | Scope             | CO₂ (Mt) | CH₄  | N₂O  | CO   | VOCs | NOₓ (as N) | SO₂ (as S) | BC   | OC  |
|----------------------|-----------|-------------------|----------|------|------|------|------|------------|------------|------|-----|
| Unger et al. (16)    | 2000      | household biofuel | 495      | 13.8 | 0.2  | 237  | 27.3 | 2.2        | 3.1        | 1.47 | 7.8 |
| Bond et al. (15)     | 2005      | wood for cooking  | 7,638    | 17.1 | NA   | 362  | 85.2 | 0.5        | 1.2        | 4.06 | 25.3|
| Bailis et al. (7)    | 2009      | traditional wood fuels | 227–506  | 4.8  | 0.01 | 86   | 14.2 | 2.8        | NA         | 1.04 | 1.8 |

*aThis analysis accounts for regrowth of sustainably harvested wood (see Section 2).

*bThe range of CO₂ emissions is due to uncertainty in the use of wood obtained as a result of deforestation caused by other factors (such as land clearing for agriculture), which is accessible to wood fuel consumers.

presented a bottom-up assessment of wood fuel consumption throughout the Global South and used published EFs (83) to estimate emissions and a range of plausible biomass regrowth scenarios to account for net CO₂ emissions.

With large variations in emissions, estimations of climate impacts also vary. Bailis and colleagues compare emissions of CFAs from traditional wood fuels to total anthropogenic emissions (as reported here: [http://edgar.jrc.ec.europa.eu/overview.php](http://edgar.jrc.ec.europa.eu/overview.php)). They estimate that 2009 emissions from traditional wood fuels included 1.04 Mt of BC, which was approximately 18% of the global total. They also find that the total emissions from traditional wood fuels in CO₂ equivalent units (CO₂e) using 100-year global warming potential were 1.0–1.2 Gt CO₂e, roughly 2% of anthropogenic emissions in 2009.

Bond and colleagues (15) do not report total emissions from traditional bioenergy, but they do report anthropogenic climate forcing from BC emissions from wood fuels. They divide estimations into high confidence and low confidence contributions. Their high confidence contribution is 220 ± 200 mW/m², roughly 30% of all anthropogenic BC forcing. The low confidence wood fuel contribution mainly consists of cloud interactions, which induce negative forcing. The net effect is −190 mW/m² (90% confidence from −400 to 100 mW/m²), which is roughly 25% of the low confidence anthropogenic BC forcing. Summing high and low confidence components results in a small positive contribution of 30 mW/m² with 90% confidence intervals ranging from −280 to 410 mW/m².

Unger and colleagues (16) report primarily high confidence results. They estimate BC emissions from household biofuels contribute roughly 82 mW/m² direct forcing: 20% of total anthropogenic BC assuming year 2000 emissions remain constant. They also estimate future impact of CO₂ and other long-lived GHGs, estimating a total annual contribution of 159 mW/m² by 2100: roughly 8% of forcing from 13 major economic sectors.

These studies concur that traditional wood fuels contribute a substantial fraction (18–30%) of anthropogenic BC and make a small contribution to total anthropogenic forcing (2–8%). However, many of the factors determining global impacts of traditional wood fuels, including basic consumption data, harvest sustainability (Section 2), and combustion EFs, are uncertain. There is additional uncertainty about the climate forcing caused by wood fuel emissions, particularly the effect of aerosol–cloud interactions (15, 16). Despite this uncertainty, individual efforts coalesced into a global effort to reduce the impact of traditional wood fuels (115). Measures include the promotion of cleaner biomass stoves and the adoption of alternative energy carriers such as LPG and electricity. We examine both in Section 4.
4. TRANSITIONS TO ALTERNATIVE FUELS AND TECHNOLOGIES

Assuring clean and efficient energy services for the 2.6 billion people currently depending on traditional bioenergy should be a global priority. The funds needed to ensure for these people access to clean cooking have been estimated to range between $2.6 and $17 billion/year (2, 116). Extrapolated to 2030, this investment represents only 0.2–1% of the $26 trillion in US global energy investments and 8–40% of the investments required for universal access to electricity (116).

Although the current efforts are still far from those needed, in the past decade there has been renewed interest in the topic, with a new global initiative, the Global Alliance for Clean Cookstoves (GACC), as well as several national initiatives promoting clean stoves and fuels including those of Mexico, Peru (117), Uganda, India, and others (118). Efforts promoting transitions away from traditional bioenergy have focused on three main approaches: (a) introduction of cleaner, more efficient traditional bioenergy technologies; (b) increased production and distribution of processed fuels (e.g., briquettes, pellets, biogas, ethanol) and stoves with which to burn them efficiently or that use other energy sources (e.g., solar cookers); and (c) increased access to LPG and electricity.6

Although conceptually simple, fully displacing traditional cooking systems has proven difficult. Alternative stoves and fuels are sometimes rejected outright or used in parallel with traditional modes of cooking. Such “stacking” of traditional and modern fuels and devices complicates efforts to shift traditional bioenergy users to more sustainable pathways and makes it difficult to quantify the impact of programs. Although our understanding of health and environmental burdens of traditional bioenergy is improving (Table 1), our understanding of the patterns of use and the drivers explaining these transitions remains limited (20, 120, 121). Specifically, the drivers, patterns of use, and implications of stacking, although noted more than a decade ago (19), have only recently been examined in detail (20, 127).

4.1. Fuel-Device Stacking: Beyond Fuel Switching

Stacking can lead to many different usage patterns: periodic use (e.g., on particular days of the week), seasonal variation in use, use on specific occasions (e.g., festivals), or simultaneous daily use. Each pattern leads to different impacts (20).

Interventions often implicitly assume that when households gain access to clean fuels and/or devices, they abandon their traditional technologies. Until recently, this conceptualization, known as the energy ladder, was the dominant model describing household energy transitions (122, 123). The model assumes that people move linearly toward modern fuels as they become wealthier, without looking back.

However, there is mounting evidence showing that many households do not follow this path, particularly in small, medium-sized, and/or rural towns. As opposed to complete substitution because of increased income or newly available fuels, many households “stack” traditional and modern fuels and devices, choosing the most convenient or appropriate option for a given task. This strategy increases the family’s options for meeting their energy needs (19). Stacking also arises because modern alternatives are imperfect substitutes of traditional options. Moreover, household preferences, incomes, fuel costs, and access all vary (20).

Table 4 summarizes the results of 11 studies of stacking after the introduction of clean fuels (electricity, LPG, and kerosene) in urban and rural locations across diverse geographical settings.

6Some programs have also advocated changes in practices, such as improved preparation and drying of fuel and structural modifications to the kitchen for enhanced ventilation (119).
and cultural and socioeconomic conditions, using different research methods. The data indicate the following:

1. In all cases, fuelwood use persisted after the introduction of clean fuels, but varied from 29% to 100% of all households, whereas stacking of both modern fuels and traditional biomass fuels ranged from 6% to 86%.

2. Stacking was more prevalent in rural and suburban settings than in large cities.

3. With the exception of studies from Nicaragua and China, demand for traditional biomass was not significantly reduced by adoption of modern fuels; in Mexico, households used more energy with stacking than with the exclusive use of traditional devices.

4. Stacking is not necessarily a transient state, but can be a long-term strategy. For example, studies show that stacking is still practiced in one Chinese community 30 years after electrification (124), in Mexico 27 years after the introduction of LPG (19), and in Botswana and South Africa 10 years after electrification and other clean fuels (39, 125). Stacking also persists even in the presence of heavily subsidized modern fuels, as illustrated in the case of Indonesia (126).

5. Stacking is strongly driven by household preferences linking specific fuel-stove combinations to specific cooking tasks. For example, staple foods are often cooked with traditional fuels even if modern alternatives exist, but people find niches for modern fuels, e.g., quick meals or reheating leftovers (20).

6. Traditional open fires often have other uses beyond cooking, e.g., space heating and low-level lighting, or other services modern alternatives are unable to provide.

Although less documented, recent studies are also reporting widespread stacking of traditional open fires and improved biomass cookstoves (127–133).

4.2. Impacts of Fuel-Device Stacking

The benefits of promoting cleaner stoves and fuels are different for users who stack fuels than for those who follow the energy ladder model. With stacking, at least three factors affect outcomes: (a) tasks conducted by the new stoves/fuels; (b) residual use of traditional stoves/fuels; and (c) changes in fueling, cooking, and other practices resulting from the new combination of cooking technologies.

Savings in wood fuels consumption provides a good example of the differences in impacts between households switching fuels and households that stack fuels. Several studies have shown that savings in biomass fuel consumption after the adoption of LPG or electricity are generally modest, particularly in periurban and rural settings. In rural Mexico, fuelwood consumption among mixed fuelwood-LPG users declined from 0 to 35%, depending on the village, with average savings of 7% (13, 134), and this pattern is expected to persist for the foreseeable future (135). Similarly, wood fuel consumption was unchanged in Indonesia after a national LPG program was implemented (126), in Northern Thailand households with access to LPG and electricity (136), and in rural China after 30 years of electrification (124). In fact, in some cases, stacking households consume more energy than non-stacking households; greater flexibility allows stove/fuel stackers to put wood fuels to new uses.

As a result of lower-than-expected reductions in wood fuel consumption, reductions in emissions and HAP may also be lower than expected. Residual use of traditional stoves/fuels can result in high concentrations of pollutants (137–139) and can mask the benefits of clean cookstoves. This is particularly true if traditional stoves and fuels are used for cooking tasks that require cooks to stay close to the stove for long periods (e.g., making traditional flatbreads such as tortilla or roti).
Table 4 Prevalence of traditional biomass use and characteristic stacking patterns in different case studies

| Country (region and population type) | HH using traditional biofuelsa | Fuel(s) introduced and % of HH using each fuel | Food preparation and fuel preference | Stacking patterns |
|-------------------------------------|--------------------------------|---------------------------------------------|-------------------------------------|-------------------|
| China (Sichuan; R) (124)f          | 100%                           | F and E; 78% for CK, 14% SH                 | F; meat, vegetables E; rice, noodles | Electricity did not decrease fuelwood use but enabled more services. Biomass use continued 30 years after electrification. |
| China (Shanxi, Zhejiang, Guizhou; R) (146) | 29–46%                        | LPG and E; 6–11% biomass with E, LPG, or coal | N.d.                                | All HH used biomass stack fuels. Use of cleaner fuels and stacking do not always increase with income. Biomass is no longer the dominant fuel. |
| Indonesia (Central Java; U, PU, R) (126) | 34%, 40%, 50%                  | LPG; 27%, 32%, 40%                           | N.d.                                | LPG increased from 6.4% to 91% of HH. There is no change in biomass use or saturation. LPG mainly replaced kerosene. There is increased LPG stacking at higher incomes. In urban areas, there is some stacking of electricity with LPG. |
| Thailand (Northern Thailand; U, PU, R) (136) | 78%, 89%, 98%                  | LPG and E; 46%, 48%, 39%                      | F and CH; glutinous rice (a main dish) E (for, e.g., rice cookers); other rice dishes LPG; stir-fried meat and vegetables CH; slow-roasted or boiled foods | Stacking is present in all settings. Biomass use decreases sharply in urban areas. There is a strong preference for biomass use. Multiple fuels are used to prepare the main meal. |
| Botswana (Maun City; U) (39)         | 86%                            | LPG and E; 79%                               | F; traditional time/energy intensive foods E, LPG; quick-cooking foods (e.g., rice, coffee/tea, chicken) | Stacking is persistent and dynamic: i.e., most families accessing modern fuels continue using wood on a long-term basis (over a decade in this study). Also, some HH already using modern fuels switch back to wood. |
| South Africa (Limpopo Province; R) (125) | 100% for CK, WH                | K and E; 22% F, K 31% F, K, E               |                                    | All HH still use fuelwood (exclusive or stacked) after 10 years of electrification and access to fuels such as K and CH. F is also used to some extent for SH and ironing. |
| Guatemala (N, U, R) (147) | 74%, 45%, 95% F and CH used in urban areas; only F in rural areas | LPG and some K in rural areas; 36%, 48%, 26% | F; tortillas and traditional maize-based dishes | Stacking in urban areas occurs in houses that still cook tortillas and other traditional maize products, mostly in small towns. In rural areas only stacking is present. |
| Mexico (Michoacán; R) (13) | 100% for CK, WH, SH | LPG; 20–43% F; tortillas, beans, and traditional dishes LPG; reheated foods, coffee | LPG is a complement rather than a substitute of fuelwood. Switching saves little fuelwood and no energy. |

(Continued)
### Table 4 (Continued)

| Country (region and population type) | HH using traditional biofuels<sup>b</sup> | Fuel(s) introduced and % of HH using each fuel | Food preparation and fuel preference | Stacking patterns |
|-------------------------------------|----------------------------------------|-----------------------------------------------|------------------------------------|-------------------|
| Mexico (Michoacan; R) (148)         | 100                                    | LPG; 41%                                      | F; tortillas, nixtamal             | LPG saturation increases from 3% to 41% in 27 years but does not replace entirely the use of fuelwood in any HH. |
| Nicaragua (U, R) (149)              | 95%, 98%                               | K; 50%, 73%                                   | K; rice and, to a lesser extent, beans F; mainly tortilla and beans | Kerosene replaces 50% of firewood consumption. Switching is driven by cooking tasks. Many HH use kerosene stoves only during the rainy season. |
| Ecuador (Cotacachi, Imbabura; R) (150) | 61–75%                                | LPG; 28–59%                                   | n/a                                | N.d.              |
| Ecuador (San Antonio, Imbabura; R) (151) | 100%                                   | LPG; 76–86%                                   | n/a                                | N.d.              |

<sup>a</sup>Abbreviations: (Population type) N, national; U, urban; R, rural. (Fuels) CH, charcoal; E, electricity; F, fuelwood; K, kerosene; LPG, liquefied petroleum gas. (End-uses of fuels) CK, standard cooking; SH, space heating; WH, water heating. (Additional abbreviations) HH, household; N.d., not determined.  
<sup>b</sup>Solid biofuels are fuelwood unless noted otherwise.  
<sup>c</sup>See Supplemental Section 7 for a brief description of each of the studies presented here.

Despite this, research also shows that well-designed stoves that are adapted to local cooking practices can effectively displace traditional stoves, resulting in significant benefits. For example, in Mexico, field studies reveal that up to 67% fuel savings, 80% reductions in HAP, and 50–80% reductions in GHG emissions were achieved from adoption of Patsari stoves (97, 134, 140). Interventions targeting mixed users (i.e., households already stacking traditional and cleaner stoves and/or fuels) have shown the best air quality improvements and fuel/energy savings (134). This indicates that the promotion of clean modern fuels and that of clean wood-burning stoves can be complementary strategies rather than competing objectives in household energy interventions.

### 4.3. Implications for Effective Clean Fuel and Stove Interventions

The benefits from clean cookstoves and fuels critically depend on the displacement of traditional stoves. However, alternative technologies have proven to be imperfect substitutes for traditional stoves. There are many reasons for this: Optimized stove designs that reduce emissions or fuel tend to be less flexible than traditional stoves and cannot be used for the same range of tasks; they may not be well adapted to some local dishes; they may be less convenient, e.g., they may require smaller wood pieces, continuous feeding, or different lighting procedures; or households may rely on numerous fuels to cope with variable incomes, prices, or availability. If the most inefficient and polluting devices are to be successfully phased out, interventions need to identify and account for the factors leading to stove stacking. This includes (a) identifying the niches of local end-uses and cooking practices that can actually be fulfilled by the clean fuel-stoves and solutions to cover
niches with the most critical impacts and benefits; (b) offering a portfolio of options and adopting more integrated approaches that include multiple fuels, devices, and improved practices; and (c) basing impact assessments on actual field performance and considering the weight of both the specific tasks fulfilled by the clean fuel-stoves and the residual end-uses and tasks still performed with the traditional fires. (20) (see Supplemental Material Section 8).

5. CONCLUSIONS: FUTURE RESEARCH NEEDS

Our knowledge of the environmental impacts associated with traditional bioenergy has improved over the past decade. For example, the relationships between wood extraction, deforestation, and forest degradation have been explored across a range of scales showing that there are indeed “hotspots” where wood fuel harvesting is likely to be driving degradation. However, in other regions, the impacts are probably lower than previously thought. This shows the importance of local circumstances in determining sustainability of traditional bioenergy.

Studies of pollution from traditional biomass combustion examine hundreds of stove-fuel combinations. They reveal wide variation between devices but show consistent patterns including lower emissions of CFAs and health-damaging pollutants for many, but not all, nontraditional stoves. The studies also confirm correlations between CO and aerosol emissions (PM, PM2.5, BC, and OC). Taken together, research on LCC and CFA emissions from traditional biomass reveals substantial net contributions to anthropogenic BC emissions (18–30%) and smaller contributions to total anthropogenic climate impacts (2–8%).

Transitioning from traditional bioenergy to exclusive use of cleaner fuels and devices has proven difficult. Prolonged stacking of devices and fuels, rather than full substitution, is more common than previously thought. Accounting for this requires a reappraisal of stove interventions and monitoring strategies: from the common approach that considers “one fuel and device,” to more integrated approaches that incorporate a portfolio of options and account for the residual use of traditional devices.

Several critical knowledge gaps persist in the environmental impacts and usage patterns of traditional bioenergy fuels and devices, which could be filled by addressing the following research priorities:

- develop consistent and up-to-date national and/or global databases for wood fuel production and consumption data, which could be gathered using periodic household consumption surveys that could be conducted by many countries;
- develop models capable of mimicking spatial and temporal patterns of LCC, validate simulations with reliable data, and project plausible impacts into the near future [other analyses have done this for different impacts (e.g., 141–144)];
- conduct more EF measurements in field conditions and/or improve simulated cooking tests so that field conditions are better replicated in the laboratory (e.g., by focusing on key cooking practices and local cooking cycles);
- develop consistent and up-to-date databases of household cooking fuels and devices, as many censuses and demographic/health surveys ask only about primary cooking fuel, which fails to capture stove stacking; modify surveys to gather information about multiple fuels and devices, resulting in more accurate analyses;
- develop research tools that examine the interplay between fuels, technology, household cooking practices, and culture in specific environmental and socioeconomic contexts;
- ensure that researchers and practitioners are aware of, and able to quantify, residual traditional bioenergy use after the introduction of alternative fuels and devices, including non-cooking end-uses and disaggregation of cooking tasks; and
• develop tools for monitoring stove acceptance, performance, maintenance, sustained use, and displacement for information about the state of the implementation and to obtain sufficient data to get it back on track if needed.

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