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Getting the numbers right: revisiting woodfuel sustainability in the developing world

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Abstract

The United Nations' Sustainable Development Goals encourage a transition to 'affordable, reliable, sustainable and modern energy for all'. To be successful, the transition requires billions of people to adopt cleaner, more efficient cooking technologies that contribute to sustainability through multiple pathways: improved air quality, reduced emissions of short-lived climate pollutants, and reduced deforestation or forest degradation. However, the latter depends entirely on the extent to which people rely on 'non-renewable biomass' (NRB). This paper compares NRB estimates from 286 carbon-offset projects in 51 countries to a recently published spatial assessment of pan-tropical woodfuel demand and supply. The existing projects expect to produce offsets equivalent to ∼138 $MtCO_2e$. However, when we apply NRB values derived from spatially explicit woodfuel demand and supply imbalances in the region of each offset project, we find that emission reductions are between 57 and 81 $MtCO_2e$: 41%–59% lower than expected. We suggest that project developers and financiers recalibrate their expectations of the mitigation potential of woodfuel projects. Spatial approaches like the one utilized here indicate regions where interventions are more (and less) likely to reduce deforestation or degradation: for example, in woodfuel 'hotspots' in East, West, and Southern Africa as well as South Asia, where nearly 300 million people live with acute woodfuel scarcity.

1. Introduction

Traditional woodfuels, specifically firewood and charcoal used for cooking, water treatment, and space 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 are closely related to several key challenges in achieving sustainable development. Roughly 2.8 billion people worldwide, including the world's poorest and most marginalized, burn wood to satisfy their basic energy needs [3], which has profound impacts on public health [4] and also contributes to forest degradation, deforestation, and climate change [5–8]. The Sustainable Development Goals encourage a transition to 'affordable, reliable, sustainable and modern energy for all' (SDG7) [9]. To be successful, this transition requires billions of people to adopt cleaner, more efficient cooking technologies, which are particularly attractive because they potentially deliver multiple benefits: improved air quality and climate change mitigation as well as reduced fuel collection or expenditure for poor households, and potential employment for stove manufacturers [10, 11].

The climate change impacts of traditional woodfuels depend on several independent factors. One is the combustion process, which releases CO_2 and short-lived climate forcers (SLCFs) like black and organic carbon (BC and OC) aerosols and methane (CH_4). In the case of charcoal, carbonization also releases CH_4 and numerous OC compounds [6]. Some commercial woodfuels are transported long-distances, which also results in emissions. Finally, the sustainability of wood harvesting, the main focus of this analysis, plays an important role. Nearly all tropical landscapes produce a measurable increment of woody biomass over time, either as new growth, or as re-growth from previous harvesting. If woodfuels are harvested below this increment, then the harvest is considered sustainable and the CO_2 emitted during combustion is sequestered by biomass growth. However, if the rate of harvest exceeds the rate of growth, then harvesting will cause biomass stocks to decline, contributing to degradation or, in extreme cases, deforestation[7]. Such harvesting is unsustainable and a fraction of the CO_2 emitted during combustion remains in the atmosphere.

Household energy interventions that promote clean and efficient stoves or fuel switching can mitigate climate change both by reducing SLCF emissions *and* reducing woodfuel consumption. However, the latter only mitigates climate change if woodfuel is harvested unsustainably. Working from the assumption that unsustainable harvesting is widespread, household energy interventions have been enlisted in climate change mitigation efforts throughout the developing world. At the time of writing, over 300 carbon-offset projects are in various stages of implementation to reduce emissions from woodfuels by disseminating more efficient stoves or promoting alternative technologies like biogas and solar cookers. Many Nationally Determined Contributions (NDCs) indicate plans to reduce non-renewable biomass (NRB). However, evidence was recently presented questioning the assumption that woodfuel harvesting is highly unsustainable [13]. Here we extend that analysis by comparing the findings from that study with claims from several hundred existing projects. We find that, if they are successfully implemented, the existing projects expect to reduce emissions by ~138 $MtCO_2e$. However, using the 'Woodfuels Integrated Supply/Demand Overview Mapping' (WISDOM) methodology, which an analytic tool that quantifies spatially explicit imbalances between supply and demand for woody biomass and has been applied in over 25 countries, we find that these projects will likely reduce emissions by 57–81 $MtCO_2e$ accounting for the same suite of climate forcing pollutants that the projects use to calculate their impact.

Thus, the carbon offsets generated by household energy interventions may be 41%–59% lower than expected. This is not to say that scarcity of woody biomass is not problematic, or that woodfuels consumption does not contribute to climate forcing. Woodfuel scarcity is most certainly a challenge throughout the global south, and woodfuel demand can contribute to degradation or deforestation under certain conditions. However, the problem is both less severe and more heterogeneous than is generally acknowledged.

Moreover, we stress that clean-burning stoves and fuels are worth promoting for reasons unrelated to forest conservation and climate change mitigation. We bring these results to the attention of researchers, development practitioners, and donors not because we advocate a halt to these types of interventions, but rather to recalibrate expectations. Woodfuel projects are unlikely to deliver the magnitude of emission reductions that project documents imply, but this analysis highlights specific geographic regions where interventions are more (and less) likely to be effective. There are woodfuel 'hotspots' in parts of East, West, and Southern Africa as well as South Asia, where nearly 300 million people struggle with acute woodfuel scarcity and substantial emission reductions (ERs) are achievable. Finally, we wish to raise the profile of this issue, by stressing that these results are estimations that require further examination and validation. In the sections that follow, we briefly review the competing narratives of woodfuel sustainability, examine the methods that researchers and analysts have developed to estimate changes in climate forcing that result from interventions, explain the methods that we utilized to carry out this analysis, review the results in detail, and discuss the policy implications of our findings.

2. Woodfuel sustainability: competing narratives

To understand the mitigation potential of clean-burning stoves and fuels, we must understand the sustainability of woodfuel extraction. Many studies have focused on woodfuel emissions, driven largely by a concern for public health and the close association between emissions of climate forcers and health damaging pollutants (see [14] for a review). Although the overall impact of aerosol emissions is still uncertain, a clear picture of the climate change impact from biomass combustion is emerging [7, 15, 16]. In contrast, few studies of carbon flows related to woodfuel harvesting have been conducted [16]. Historically, woodfuel demand was considered a major driver of deforestation [17, 18], but this position was challenged decades ago [19, 20]. More recent local or regional assessments find conflicting results [21–25], suggesting that geography is an important factor in determining woodfuel sustainability. The IPCC's Fourth Assessment claimed that 10% of global woodfuel is harvested unsustainably, [26, 27] but the Fifth Assessment stressed that net emissions from woodfuels are still unknown [25].

Despite many years of interventions in the household energy sector in the developing world, we have a fairly limited understanding of the environmental implications of woodfuel demand. On one hand, there is a compelling narrative of environmental destruction in which demand from impoverished woodfuel users

[7] There are multiple definitions of degradation or deforestation; for a review of the terminology see [12].

outstrips nature's supply, leading to deforestation and degradation [28, 29]. On the other hand, we have a more tempered story of resilient forests, 'trees on farms' [30], and woodfuel-users who respond to scarcity by switching to lower quality fuels or augmenting wood supplies through agroforestry [19].

These conflicting narratives have developed over the past few decades against a backdrop of alarming tropical deforestation. Between 2001 and 2013, over 110 million ha of tropical forest were cleared [31]. There is evidence suggesting that woodfuels play a role in degradation or deforestation in specific locations [24, 32], typically working in conjunction with other pressures like such as livestock production or the expansion of agriculture and transportation networks [30, 33–35]. However, quantifying the impact of woodfuel harvesting on deforestation and forest degradation is difficult. Woodfuel extraction occurs in diverse social and ecological settings. Demand depends on local cooking practices, species composition, and the availability of alternative fuels. Few countries collect regular data, and there is some seasonality in demand that can make one-time surveys misleading. Woodfuel supplies vary with stock, productivity, and accessibility of diverse types of woody biomass. Woodfuels are extracted from many types of land cover: forests, agricultural lands, and other 'trees outside forests,' such as live fences, home gardens, and roadside commons. Moreover, landscapes utilized for woodfuel extraction are rarely isolated from other pressures. They may be subject to timber extraction, agricultural expansion, grazing, or other uses.

Supply systems vary greatly in length, from those involving individual users who extract material from within a few kilometers of their homes for their own use to complex networks consisting of thousands of harvesters moving tons of wood through middlemen to commercial markets hundreds of kilometers away. Finally, the landscape's response to harvesting is dynamic and non-linear. The structure of tree stands may change over time, driving people to adjust the quantity they harvest, or shift extraction sites altogether [36–38].

These complexities raise challenges for policy makers and researchers, which are reflected in the lack of clarity in current methodologies designed to estimate carbon savings from cookstove projects described below [39–42]. As our assessment demonstrates, most woodfuel interventions appear to be overstating the extent to which woodfuels contribute to deforestation, and, by extension, their mitigation benefits. We expand on this below.

3. Review of existing woodfuel-based mitigation projects

We identified woodfuel-based carbon-offset projects using several publically accessible databases including the Gold Standard (GS) Foundation project registry [43], the UNEP DTU Partnership's listing of Clean Development Mechanism (CDM) and Programme of Activities (PoA) projects [44], and the United Nations Framework Convention on Climate Change (UNFCCC)'s CDM project database [45]. These projects generate offsets by reducing the use of NRB, which is the term used by carbon market practitioners to define unsustainably harvested woodfuels.

At the end of 2014, we found 286 woodfuel-based offset projects at various stages of development worldwide consisting of a mix of individual project activities (PAs) and 'component project activities' (CPAs) within distinct PoAs[8]. Of these, 75 were voluntary projects registered with the GS Foundation, two with the Voluntary Carbon Standard (VCS), and one with the American Carbon Registry (ACR) [43]. The remaining 211 projects were developed either as PAs or CPAs under the UNFCCC's Clean Development Mechanism (CDM) and 41 of these have GS certification [44][9]. To put this in perspective, these projects represent less than 1% of carbon offset projects in the CDM, which was always dominated by large-scale projects targeting industrial gases [44]. However, woodfuel-based carbon-offset projects make a substantial contribution to voluntary credits, generating over $160 million in trade between 2007 and 2014, which was nearly 10% of the cumulative value in the voluntary market [48].

We include all projects that are registered in the pipeline and exclude projects that had been withdrawn or rejected. We found projects from 51 different countries. The regional breakdown by number of projects, expected ERs during the project lifetime, and ERs issued by December 2014, is shown in figure 1. Project locations are shown in figure 2.

To quantify the offsets generated by reducing NRB consumption, project developers follow specific methodologies. The methodologies undergo expert review and public comment prior to acceptance by the UNFCCC and voluntary registries. After methodologies are accepted, project developers submit project 'design documents' (PDDs, PoA-DDs and CPA-DDs) describing the methods they utilize, and third parties audit every project to ensure adherence to the specific methodological requirements. Despite numerous checks on the system, the methodologies to quantify ERs and NRB are vague and subject to multiple interpretations, which leads to inconsistent applications and results in large systematic overestimations of NRB. In the following section, we briefly review the approaches used to determine NRB.

[8] A PoA can encompass one or more CPAs. For a full explanation of UNFCCC regulations, readers may refer to the UNFCCC's 'Glossary of CDM terms' [46].

[9] For a detailed exploration of carbon markets and types of offset projects readers can refer to [47].

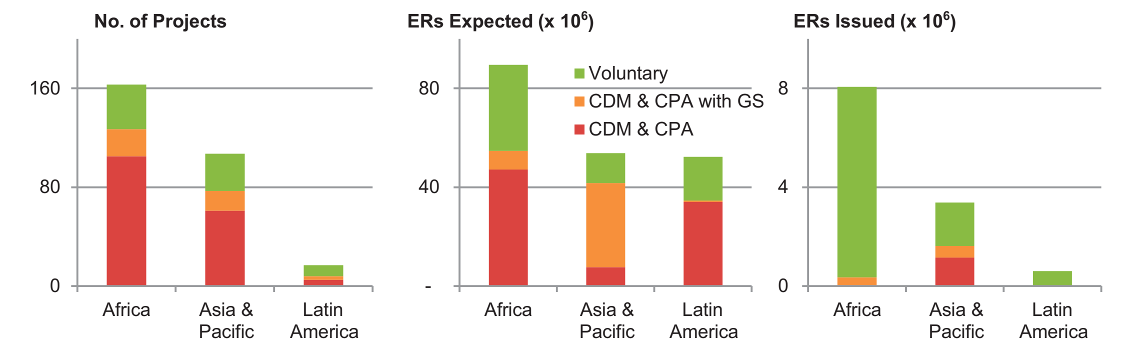

Figure 1. Woodfuel-related carbon offset projects registered or in the 'pipeline' in December 2014.

Figure 2. Siting of projects generating carbon offsets by reducing consumption of NRB; points are sized proportionally to the volume of C/VERs expected during the lifetime of the projects.

4. Assessing NRB in carbon offset projects

There are two main categories of projects using NRB reduction to generate carbon offsets: those producing offsets for the UNFCCC's CDM and those producing offsets for voluntary markets. Both CDM and voluntary markets have developed detailed methodologies to define and calculate NRB, which we examine in this section.

4.1. UNFCCC

The UNFCCC first introduced a CDM methodology to quantify ERs from NRB in 2005, soon after the CDM itself went into effect. The methodology, AMS-I.C, was a generic methodology introduced for projects displacing fossil fuels with renewable energy in thermal applications (supplementary table 2, available at stacks.iop.org/ERL/12/115002/mmedia). The sixth version of this methodology permitted displacement of NRB as well as fossil fuels, but lacked details about how to calculate NRB, and it was dropped. In 2008, two new NRB methodologies were introduced (AMS-I.E and AMS.II.G), which allowed woodfuel projects to gain a stronger foothold in the CDM. In 2011 two additional methodologies were added: one accounted for methane ERs, which catered to biogas projects that reduce NRB consumption and a second that promotes water filters to reduce NRB consumption by assuming that filter adoption reduces reliance on woodfuels to boil water.

AMS-I.E and AMS.II.G are the main methodologies used with NRB projects in the CDM. Each is based on a ruling from the 23rd meeting of the CDM Executive Board (EB) [49] relying on differentiation between NRB and demonstrably renewable biomass (DRB). Under this approach, DRB is defined by one of several conditions (described in the supplementary material).

Once DRB is identified, NRB is defined as whatever biomass is *not* DRB. However, realizing that this may not be sufficiently conservative, the methodologies include additional considerations. Biomass that is not DRB can be considered NRB when two of these three trends are observed:

- Time or distance required to gather woodfuel is increasing;
- Prices are increasing
- Biomass is declining in quality.

Once NRB and DRB are distinguished, the fraction of NRB, which indicates the percentage of woody biomass that is unsustainable, is defined as:

$$fNRB = \frac{NRB}{NRB + DRB}. \quad (1)$$

4.2. UNFCCC default values

More recently, in order to encourage more projects in countries that did not attract much CDM activity, the CDM EB suggested fNRB default values be used for least developed countries (LDCs), small island developing states (SIDs), and other countries with few projects [39]. Currently, the EB has defined 58 national default values ranging from 40% in Bhutan and Cuba to 100% in Mauritius, Bahrain, Comoros, and Djibouti (see supplementary table 1 for all values). The default calculation utilizes equation (1), and assumes DRB can only originate from protected forest areas as defined by the Food and Agriculture Organization (FAO)'s 2010 Forest Resource Assessment [50].

4.3. Gold Standard (GS)

Woodfuel projects made a rapid entry into the voluntary carbon market through the GS certification scheme. The GS methodology was released in 2008, a few months ahead of the CDM methodologies described above. Like the CDM, the GS methodology allowed for multiple approaches to assess NRB and evolved over time to allow for the use of default values in some cases. The first version of the GS methodology allowed NRB assessment by following UNFCCC's DRB approach, supplemented by data from field surveys, literature, and mapping. However, the methodology makes provisions for alternative approaches depending on information available in the project area. They suggest a quantitative approach if there is sufficient data, and allow project developers to adopt a qualitative approach if data is lacking (both approaches are described in the supplementary material).

The qualitative approach suggests the use of 'Satellite imagery, combined with field surveys, pertinent literature reviews, and expert consultations' to determine the NRB fraction [51, p. 29]. Subsequent versions of the GS methodology, which were released in 2010 and 2011, introduced small changes, but the overarching approach remains the same [40]. In 2013, the GS released a Simplified Methodology for Efficient Cookstoves [52], which allows projects to use the UNFCCC default values. Active projects submitted under various GS methodologies are listed in the supplementary material.

4.4. Methodological shortcomings

Both UNFCCC and GS methodologies have several shortcomings. First, the UNFCCC and early GS methodologies require land to be under 'sustainable management practices' in order for harvesting to be demonstrably renewable, but they offer no guidance about what constitutes sustainable practices. Management of land from which woodfuels are extracted is rarely formalized [19, 53, 54]. However, lack of formal management does not necessarily mean that biomass resources are exploited unsustainably. Informal rules governing access may be in place to discourage unsustainable exploitation, but such rules are often unrecognized by outsiders [54]. The qualitative option in the GS methodology is equally vague. Similarly, the UNFCCC's default values equate sustainable management with national parks, game reserves, wilderness areas, and other legally established protected areas, making an implicit assumption that land without these designations cannot be sustainably managed.

In addition, the suggested approach allows for no middle ground. In areas that are not demonstrably renewable, it implicitly assumes wood extraction is completely non-renewable. This is equivalent to assuming that the land has *no regenerative capacity*, which is a gross overstatement of land degradation. In most cases, when woody biomass is removed from a given area of land, that land can continue producing woody biomass. If it has been overexploited or degraded, it may produce woody biomass at a slower rate than in the past, or with a different species composition, but it is unlikely to remain barren in perpetuity. An exception of course, is if forests or woodlands are cleared to meet woodfuel demand, but subsequently converted to cropland. However, under those circumstances, reduced NRB consumption will not result in emission reductions because other pressures are preventing regrowth of the wood that is harvested.

The GS quantitative approach is somewhat more realistic. It accounts for the productivity of woody biomass by including a mean annual increment (MAI) in the assessment of NRB. However, the assessments typically apply a single MAI across large regions, up to, in many cases, entire countries. These average values fail to account for heterogeneity in growth rates and assume that the people harvesting wood exploit all regions equally. In reality, people are more likely to exploit areas with more abundant woody biomass, which would have higher growth rates than surrounding areas with low stocks of woody biomass.

Finally, trends of increasing time, distance, or prices, may indeed be indicative of scarcity. However, this scarcity may be induced by factors that are independent of woodfuel demand. Urbanization, crop expansion, and grazing pressure are all recognized drivers of land cover change [24, 33] that can decrease access to woodfuels, increase collection times, or raise prices and drive users to opt for lower quality fuels. However, these are not necessarily indications that woodfuel extraction itself is unsustainable. In addition, price trends may simply reflect inflation. For example, in Kenya, the average nominal price of a 4 kg tin of charcoal increased three-fold over the past decade, but adjusting for inflation shows that the price has not changed in real terms [55]. Thus, evidence of increasing prices should be treated with care.

5. An alternative approach

Here we present an alternative method to assess woodfuel sustainability. The 'Woodfuels Integrated Supply/Demand Overview Mapping' (WISDOM), accounts for some of the complexities of balancing traditional wood harvest for energy with associated CO_2 emissions. For example, it uses spatial analyses to account for woody biomass supplied by various land cover classes as well as landscape features, deforestation patterns, and other factors that affect accessibility to woody biomass resources. The methodology has been described in numerous peer-reviewed articles [13, 56–59] and applied in over 25 countries [60]. The recent pan-tropical analysis [13, 59] produced a range of estimates dependent on several key assumptions such as whether by-products of deforestation caused by agricultural expansion were used as fuel and the degree to which people optimize woodfuel harvesting based on the sustainable yield of woody biomass.

The pan-tropical analysis was particularly sensitive to the utilization of accessible deforestation by-products. When deforestation driven by agricultural expansion occurs in regions that are accessible to woodfuel-dependent populations, there is strong evidence that some cleared biomass is utilized as firewood or to make charcoal [13, 16], but the actual quantity of material utilized in a given location is not known. Lacking data, the pan-tropical assessment considered two scenarios. In Scenario A, deforestation by-products generated in accessible regions are not used and woodfuels are harvested entirely from other sources. NRB_A defines the quantity of non-renewable biomass when deforestation by-products are not used at all. In Scenario B, accessible deforestation by-products are utilized as fuel. This scenario results in two components of woodfuel supply: one component (B_1) consists of the deforestation by-products used to meet a fraction of woodfuel demand and the other component (B_2) consists of wood harvested from other sources required to fully satisfy demand after deforestation by-products are exhausted. Component B_1 is non-renewable by definition, defined as NRB_{B1}. If B_2 exceeds woody biomass growth in a given region, the excess quantity is non-renewable, defined as NRB_{B2}. In each case, fNRB is defined as the ratio of NRB to total consumption.

6. Quantifying overestimations of CERs and VERs from woodfuel-based carbon offset projects

To compare ERs claimed by carbon-offset projects to ERs that would be generated from alternative fNRB estimates, we reviewed design documents from 287 projects. The documents indicate a total 138 $MtCO_2e$ of emissions reductions are expected. Of this, 12.1 $MtCO_2e$ had been verified and issued (figure 1). Some GS methodologies include CH_4 and N_2O in their offset calculations; however, only 6% of projects utilize these methodologies and the total reductions expected from CH_4 and N_2O are less than 1% of the total. Thus, the vast majority of ERs result from CO_2 emissions reductions linked directly to reduced consumption of NRB. Figure 3 shows the average of fNRB values (± standard deviation) used in carbon-offset projects with the number of projects in each country given on the horizontal axis. It also shows the range of geographically specific fNRB estimates derived from the pan-tropical analysis (black dashes and gray bars)[10]. The lower bound shows the results of Scenario B_1, the middle value shows the results of Scenario A, and the upper bound shows the net result of $B_1 + B_2$. In many cases, $fNRB_A$ is equivalent to $fNRB_{B1+B2}$.

The fNRB values used in project design documents to calculate ERs range from 43% to 100% with a median of 88%. The values derived from the pan-tropical WISDOM analysis are much lower, with a median value of 24%–29%. There are just three countries in which the upper bound of fNRB derived from WISDOM match or exceed fNRB used in project documents: Pakistan, Cameroon and Nicaragua. In addition, in some countries, WISDOM-derived fNRB values vary widely. This is largest in parts of Central America and West Africa, which both experience high rates in deforestation in accessible regions. If deforestation by-products are not used as woodfuel (Scenario A), fNRB is relatively low because high woody biomass productivity ensures woodfuel demand can be met sustainably. However, if people do use deforestation by-products (Scenario B), which are unsustainable by definition, then fNRB is quite high because there are sufficient forest clearance by-products to satisfy much or all of demand[11]. It is difficult to reduce emissions with woodfuel interventions alone under these conditions because deforestation is likely driven by demand for cropland and pasture [24]. In such cases, reducing woodfuel demand without addressing other drivers would have minimal impact on forest loss.

In other countries, the range of uncertainty in fNRB is narrower. For example, some countries have very little deforestation and no available by-products (e.g. India and China), resulting in similar outcomes for both Scenarios A and B. Other countries experience a lot of deforestation (e.g. Brazil, Democratic Republic of Congo, and Indonesia), but the by-products are inaccessible to the majority of woodfuel users. Finally, in

[10] We used fNRB from the subnational unit (state or province) where projects were located. If projects were national in scope or documents did not specify the sub-national unit(s), we used national fNRB.

[11] Cameroon is an extreme example: fNRB derived from Scenario A is zero, while fNRB from Scenario B is 100%.

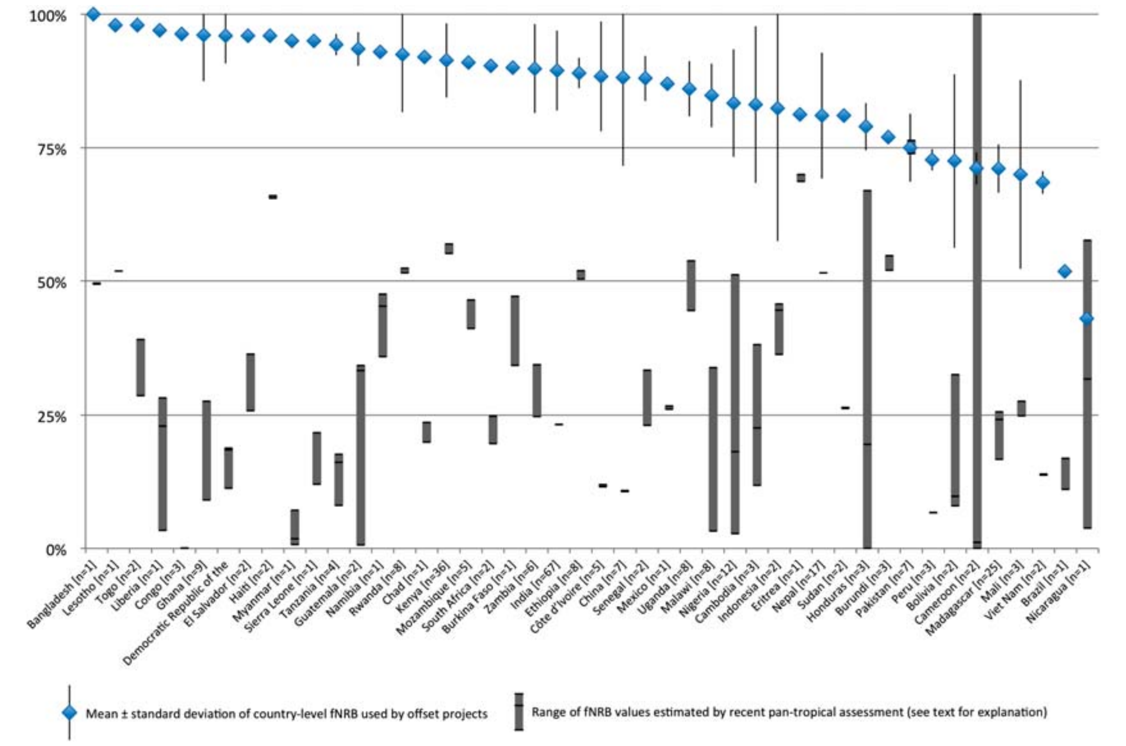

Figure 3. Mean (± standard deviation) fNRB values used in offset projects compared to range of values derived from WISDOM at the same locations.

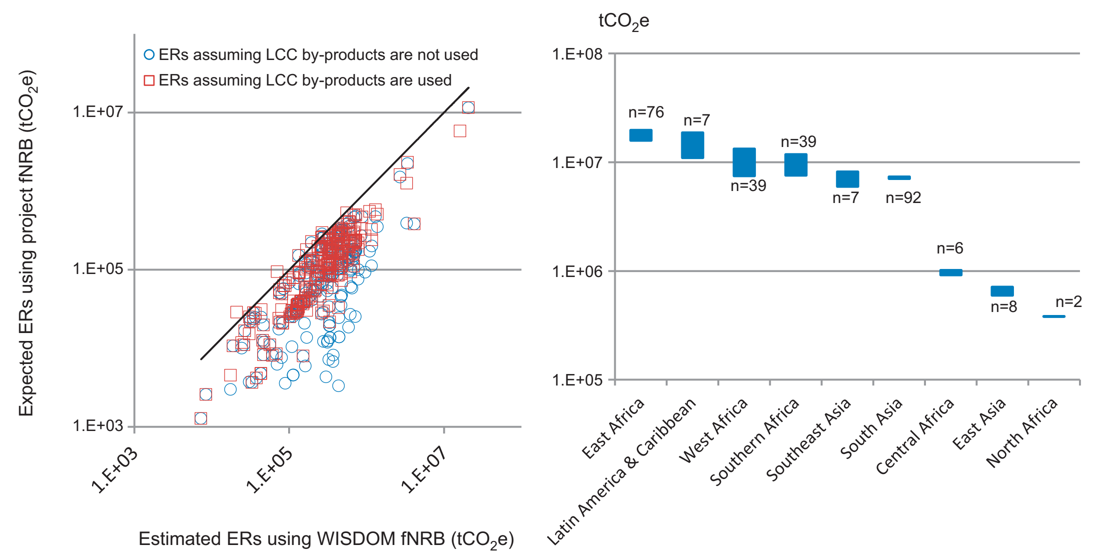

Figure 4. Expected vs. estimated ERs by project (left) and aggregate overestimations of ERs by region (right). Note that both plots use logarithmic scales.

some places, deforestation occurs in accessible regions, but the volume of by-products is lower than overall woodfuel demand, so people must rely on direct harvesting regardless of whether by-products are utilized (e.g. much of East and Southern Africa).

Overestimation of fNRB shown in figure 3 results in considerable overestimation of ERs from offset projects. To calculate the extent, we replaced the values of fNRB used to estimate ERs (described in the supplementary material), with geographically specific values derived from the pan-tropical WISDOM analysis (fNRB values from regions where projects are implemented are provided in the supplementary material). The results are shown in figure 4. The plot on the left shows expected ERs reported in each project plotted against the ERs calculated by substituting fNRB with the estimate from the pan-tropical NRB assessment. The line indicates where equal estimates would fall. In the majority (98%) of cases, the ERs expected by project implementers are larger than the ERs that are likely to be generated based on the WISDOM assessment. The magnitude of overestimates is shown in the plot on the right. The bars show the upper and lower range of values derived from Scenario A and B respectively. Taken together, PDDs overestimate ERs expected from NRB demand reduction by 57–81 $MtCO_2e$ (41%–59%). We also note that there is a negative correlation between the WISDOM-based fNRB value and the relative magnitude of the ER overestimation. This is a logical outcome of the analysis; when WISDOM-based fNRB values are high, differences between the ERs derived from WISDOM-based fNRB values and ERs reported in the PDDs are smaller than when with WISDOM-based fNRB estimates are low.

7. Conclusion

Nearly 300 woodfuel projects have been implemented in an effort to mitigate climate change while also delivering co-benefits like reduced household air pollution. These projects could be viewed as forerunners of more ambitious activities that will be implemented to achieve SDG7 as well as many NDCs. However, we find that ~80% of these projects are likely overestimating the mitigation potential of their activities by using excessively negative assumptions about the sustainability of woodfuel harvesting. The projects are unlikely to reduce deforestation and/or forest degradation to the degree promised. We suggest that project developers and investors recalibrate their expectations by adopting more conservative values of fNRB, based on spatially explicit estimates of woody biomass productivity and accessibility. While this will reduce revenue available from carbon offsets, it will also avoid disappointment and disillusionment from under-performing projects. In addition, the spatially explicit approach provides project developers with a useful tool to identify locations where interventions are likely to achieve the largest emission reductions. For example, there are woodfuel 'hotspots' in parts of East, West, and Southern Africa as well as South Asia, where nearly 300 million people struggle with acute woodfuel scarcity.

We also acknowledge some limitations to the spatial approach. First, the methodology requires expertise in geo-spatial analysis, and it would not be practical to incorporate into carbon-offset methodologies like those described in the appendices to this paper. In addition, the processes that are modeled, summarized in section 2, require supply and demand data that is often highly uncertain. Moreover, the model should undergo calibration and testing in order to develop greater confidence [61], but to do so on a global scale is very difficult. Nevertheless, some straightforward procedures can help. First, fNRB estimates can be used to project biomass decay over time. If high fNRB values were as widespread as registered carbon-offset projects imply, we would observe extensive woodfuel-driven land cover change. Second, we could use coarse spatial resolution imagery (e.g. MODIS) and search for temporal trends in vegetation cover over global woodfuel hot spots and look for correlations between high NRB and land cover change. However, with multiple drivers of land cover change present in most locations, linking land cover change specifically to woodfuel demand remains open to debate.

Finally, we acknowledge our suggested recalibration of expectations from woodfuel interventions might result in lower carbon revenues flowing to clean and efficient stoves or fuel switching projects. However, rather than choking off activity, we hope this research serves to boost the growing debate about how to bring more robust finance to clean and efficient stoves or fuel switching interventions. We should not rely too heavily on forest conservation and associated emission reductions as a source of finance for traditional energy interventions[12]. Such interventions carry many potential benefits including reduced emissions of household air pollution and short-lived climate forcers and reduced fuel collection or expenditure for poor households, as well as employment for stove producers. While these benefits are not monetized like carbon offsets, there are potential pathways for revenues to flow that would replace, if not exceed, the loss in carbon revenue if more realistic fNRB values are adopted.

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