Updated fNRB Values for Woodfuel Interventions

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1. Executive Summary

1. This executive summary outlines key findings from the MoFuSS model (Modeling Fuelwood Saving Scenarios), applied to various countries in the Global South. It presents business-as-usual scenarios extending to 2030, with a spatial resolution of 1km. MoFuSS is a peer-reviewed simulation model initially developed to estimate CO_2 emission reductions from traditional woodfuel harvest and use, comparing business-as-usual with intervention scenarios. To ensure thoroughness, MoFuSS has evolved into a sophisticated geospatial modeling tool, incorporating various land change drivers, woodfuel demand sources, and end-user technologies.

2. For this analysis, MoFuSS was simplified to estimate the fraction of Non-Renewable Biomass (fNRB) across three hierarchical administrative levels in 75 countries of the Global South including 98% of the global population using wood and charcoal as their primary cooking fuel. fNRB is a key metric used to calculate carbon emission reductions from interventions that reduce demand for fuelwood or charcoal. It is defined as the ratio of losses in aboveground woody Biomass (AGB) stocks over a specific period to the total woodfuel (fuelwood plus charcoal) consumption in the same period.

1.1 Summary of results

3. The global average fNRB of the 75 countries included in the assessment is 32% ± 18% (spatial mean ± standard deviation). Regionally, Sub-Saharan Africa (SSA) has the highest fNRB, at 39% ± 17%, followed by Latin America and Asia, with 33% ± 14% and 17% ± 21% respectively (**Table ES1**).[1]

Table ES1: Regional fNRB values

Region	fNRB	Std deviation
Asia	17%	22%
Latin America	33%	14%
Sub-Saharan Africa	39%	17%
Global	32%	18%

4. At the national level, we find fNRB values ranging between 1% and 70%, with the interquartile range (representing the middle half of national values), falling between 21% and 40%. The highest national fNRB estimates occur in semi-arid countries in the Sahel, followed by several countries in East and Southern Africa and East Asia. See **Table 5** in the Results section for the full list of national fNRB estimates.

5. To estimate urban fNRB, we assume that woodfuels consumed in towns and cities are harvested and transported from rural areas. As they are exploited commercially, urban fuelwood and charcoal tend to have higher impact than wood harvested for subsistence use by rural households. To account for this, we carry out a simple statistical analysis that takes a weighted average of the rural administrative units with higher fNRB. This results in estimates of urban fNRB that are several percentage points higher than the national average. For example, we estimate that Sierra Leone's national fNRB is 40% ±

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[1] We present global and regional averages for illustrative purposes. National and sub-national values are more appropriate to assess project-level impacts.

15%. fRNB in its four main administrative units ranges from 36 to 50, and we calculated that fNRB in Freetown and other urban centers would be 42% ± 15%.

1.2 Key changes between October 2023 and this report

6. After the preliminary fNRB results for Sub-Saharan Africa were submitted to the CDM in October 2023, several key assumptions were changed in response to feedback from key stakeholders. In addition, the scope of the assessment was expanded to encompass the entire Global South. These changes required the use of different input datasets and several modifications to the model itself.

7. For clarity, below we list the most critical modifications and new datasets recently introduced, ranked by their impact on the differences between the new results and those presented in October 2023 for Sub-Saharan Africa.

    a) **Population maps**: We transitioned from HSRL to WorldPop (https://www.worldpop.org/) to include countries not covered by HSRL, such as China and others in Asia and Africa.

    b) **Revegetation Growth Curves**: The submodule for generating revegetation growth curves was completely recoded. In the previous approach, we estimated growth functions from the IPCC's biomass stock estimations. However, we discovered that this led to growth rates that observed standing stocks of biomass in two of the 680 land-cover categories. In addition, in very arid areas, we found that available biomass was less than the model's minimum harvestable threshold (1 ton/ha for charcoal production and 0.1 ton/ha for gathered fuelwood), which caused the model to output physically impossible negative harvest and fNRB values in a small number of pixels. This was corrected to avoid those outputs.[2]

    c) **Regional boundaries in Sub-Saharan Africa**: We have redefined the regional boundaries in Sub-Saharan Africa based on recent reviews of international illegal woodfuel trade, and we have increased the friction parameter for crossing international borders.

    d) **Woodfuel consumption**: All fuelwood and charcoal demand figures have been thoroughly reviewed in response to public comments.

1.3 How to interpret results

8. In geospatial analysis and modeling, the resolution of map layers being processed, and the time of analysis are of paramount importance. Even though we are presenting results by administrative units, as requested by CDM, all input, temporal, and output layers in MoFuSS are invariantly a rectangular matrix of pixels, or so called "raster maps." The size of each pixel or cell becomes important because they represent features in the real world. In the present analysis, all input layers at 30, 90, 100, 300 and 500m were resampled using appropriate procedures into 1 km pixels.[3]

9. Regarding temporal resolution, MoFuSS operates with annual increments from 2010 to 2050. The summary results for the current decade (2020-2030) are provided as per the requirements of the CDM. MoFuSS is a dynamic geospatial model, which means it reflects temporal changes in land use. For

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[2] Throughout the report we use "tons" as shorthand for "metric tons".

[3] Note, many landscape and climate models global coverage work at resolutions of 10 or 300 km per pixel.

instance, an area cleared for charcoal production in the first year is recorded as deforested during that year but may experience regrowth in subsequent years. Employing decadal intervals to report data is a conservative approach (towards higher values of fNRB) as revegetation can often extend beyond a decade, particularly in regions where woodfuel demand is projected to decrease to zero by 2050.

1.4 Uncertainty

10. Several of the input parameters are uncertain, which propagates through the analysis, affecting the key outcomes. We demonstrate this uncertainty by running Monte Carlo simulations. In this assessment, we focused on uncertainty in growth rates, which is the main driver of uncertainty in the model. We report uncertainties as standard deviations of harvest, NRB, and fNRB resulting from 30 Monte Carlo model runs in which each run includes a randomly selected value of “r_{max}”, which is the parameter that defines the shape of the biomass growth functions for a given ecological zone, from a truncated normal distribution of potential values. [4]

1.5 Validation and next steps

11. Validating fNRB estimations on a global scale is not feasible, because it is difficult to attribute observed changes in above ground biomass(AGB) to specific causes at such broad scales. However, it is possible to validate assumptions at smaller scales by looking at past changes in tree cover in known woodfuel extraction areas. It is also possible to use observed changes in tree cover to exclude unrealistically high fNRB values by assuming all change is due to wood harvesting. Moreover, in extensive cookstove projects that significantly decrease woodfuel demand, variations in AGB trends before and after the intervention might eventually become detectable through remotely sensed data.

12. All of these are potential paths to validate the results presented in this assessment. While validation was not part of this assignment, the MoFuSS developers are planning to undertake a series of validation studies in the coming year. The MoFuSS team is currently exploring collaborations with researchers who develop high-resolution tree cover and tree growth maps including CTrees and Chloris Geospatial. We anticipate initial results by mid-2025.

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[4] The distribution is truncated to avoid including negative growth rates, which are not possible.

2. Introduction

13. This report describes the development of new default values for the *fraction of non-renewable biomass* (fNRB), which will be used to evaluate emissions reductions from interventions that displace unsustainable consumption of fuelwood and/or charcoal.

2.1 What is fNRB?

14. Wood can be considered a conditionally renewable resource [1]. Trees grow naturally in many environmental conditions and if wood is harvested at or below the rate at which it naturally regenerates, then harvesting is sustainable. However, if more wood is harvested than the landscape can replace, as is often the case in low- and middle-income countries (LMICs) where people rely heavily on fuelwood and charcoal, harvesting is not sustainable and tree cover will decline over time. This causes landscape degradation and may also contribute to long-term deforestation. fNRB is a measure of the relative amount of wood that is harvested above the landscape's natural rate of regeneration.

15. Interventions that support transitions to more efficient cooking practices can reduce forest degradation — as well as climate-warming emissions — because trees that would have been harvested if the intervention had not been introduced, remain standing. Likewise, any carbon that would have been emitted as CO2 remains sequestered in those trees. Reliable estimates of fNRB ensure the integrity of carbon emission reductions from clean cooking interventions because real emission reductions are only attributable to the fraction of harvested wood that would not have regenerated naturally. Higher values indicate that large percentages of wood harvest are non-renewable and successful interventions can claim higher emission reductions. Conversely, lower values of fNRB indicate that smaller percentages of wood harvest are non-renewable, and interventions can claim fewer emission reductions. However, if projects rely on fNRB estimates that are higher than the actual value, then they are claiming more emission reductions than their projects are achieving, which damages mitigation efforts and risks the reputation of all clean cooking activities.

2.2 How is fNRB used in carbon offset methodologies?

16. fNRB has been integral to carbon offset methodologies for woodfuel interventions since the first projects were developed in the late 2000s. However, the first methodologies relied on vague, semi-qualitative approaches to determine fNRB, which likely contributed to overestimates of the mitigation potential of these activities. For example, the Clean Development Mechanism's (CDM's) first clean cooking methodologies, released in 2008, required project developers to "determine the share of renewable and non-renewable biomass" by assuming that renewable biomass originated on land under formal management or land set aside for conservation purposes and that biomass coming from other regions was non-renewable [2,3]. This dichotomous approach did not account for the many trees that grow in areas that are not under formal management or set aside for conservation. Voluntary methodologies adopted slightly more quantitative and prescriptive approaches to assess fNRB, but still resulted in inaccurate estimations. For example, the Gold Standard's "Methodology for Improved Cook-stoves and Kitchen Regimes V.01" also released in 2008, suggested that project developers "Use credible information sources, field surveys, or both, to ascertain the amount of woody biomass that is re-generating each year" in the project area [4]. The methodology included a relatively simple equation to estimate fNRB based on a number of parameters; however, it offered no guidance about what information is "credible" or how to design field surveys to determine woody biomass regeneration rates accurately. Woody biomass growth rates cannot be determined through traditional surveys. Field

assessments are quite difficult and require observation of multiple sites over many years, which is beyond the capacity of most project developers.

17. Over time, both CDM and voluntary methodologies were modified to remove some of the guesswork that characterized the first methodologies. In 2017, the CDM released "TOOL30 - Calculation of the fraction of non-renewable biomass", which has since been modified several times [5]. The latest version of TOOL30 suggests two ways to assess fNRB. The first option is to use 30% as a conservative default value, which is based on the results of research designed by this team together with other colleagues [6]. That research used the WISDOM model [7], which is explained in more detail below. The second option calculates fNRB by using a similar approach as the Gold Standard's 2008 methodology but removes some ambiguity by providing more guidelines and suggesting specific data sources. In addition, if project developers use the second option, they are asked to compare their estimates to "relevant scientific literature" and to "justify any differences". However, it is not clear whether this comparison has been enforced by verification bodies and whether it resulted in any downward adjustments of fNRB claims. We propose changes to TOOL30 in the Results section below.

2.3 The first Global fNRB Assessment

18. The 30% default value for fNRB recommended in TOOL30 was based on research published in 2015 using the WISDOM model [6]. WISDOM uses a snapshot in time to estimate imbalances in wood supply and demand. In the 2015 study, together with colleagues, we constructed a pan-tropical model that estimated sub-national fNRB values in 1st-level administrative units (e.g. provinces, states, etc.) in 90 countries. The model used global datasets for wood supply and demand which were the best available at the time. The average fNRB across those 90 countries was roughly 30%, which inspired the conservative default value recommended by TOOL30. However, results showed substantial geographic variation in fNRB values, which raises doubts about the suitability of a single global default. In some well-forested or sparsely populated areas, fNRB was considerably lower than 30%, while "hotspots" in East Africa and South Asia had fNRB values exceeding 50%. The majority of sub-national areas had fNRB values between 20 and 40%. Woodfuel projects registered at the time typically claimed between 80 and 100%, which has raised concerns about over-crediting and raised doubts about the value of carbon credits from clean cooking [8].

2.4 Reassessing fNRB

19. The integrity of emissions reductions is considered paramount to a functioning carbon market. The WISDOM-based analysis influenced clean cooking methodologies via TOOL30, but only as an option that few if any project developers have used. Some large carbon offset buyers have used the 30% global average from that assessment to set a cap on what future projects can claim. Other market actors have called for more national or sub-national default values. Such values were published with the 2015 WISDOM assessment. However, the input data used in that study are outdated and the key assumptions used may no longer be applicable.

20. To fill the need for new default values, CDM commissioned this research. The objective is to update fNRB estimations using the latest available data on woody biomass supply and demand. This assessment uses the MoFuSS model, which was developed by scientists from the National Autonomous University of Mexico (UNAM) and Stockholm Environment Institute (SEI) [9,10]. MoFuSS relies on the same basic concepts used by WISDOM, with several key differences. Where WISDOM uses a snapshot in time, MoFuSS runs multi-year simulations, which allow users to compare intervention and non-intervention scenarios that incorporate dynamic variables like population growth, urbanization, and

land cover change. In addition, though it requires some expertise to run, MoFuSS is built with freely available software using open-source code, making it transparent and accessible. We provide links to the code and other key resources in Appendix 1.

21. MoFuSS is a bottom-up spatial model that can be aggregated to any level, allowing for fNRB estimates to be made for any administrative unit (districts, counties, states, provinces, etc.) as well as project-specific areas that cut across administrative boundaries. In addition, the model developed for this project relies on harmonized global datasets that are regularly updated, which will make it easy to periodically update the fNRB defaults. While these are clear advantages over previous approaches to fNRB assessment, MoFuSS is a complex model, and specialized knowledge is required to understand and interpret the input data, intermediate outputs, and final results. In the sections that follow, we review the basic architecture of the model, key assumptions, and sources of data and results.

2.4 Key assumptions in MoFuSS

22. MoFuSS relies on several dozen parameters to model land cover change associated with woodfuel harvesting. Here we list and briefly describe the main assumptions that MoFuSS uses to estimate non-renewable biomass demand in a given locality [See appendix 1 and 2 for a full description].

2.5 Biomass stocks

23. This data tells us how much biomass exists in a pixel in the initial year of the simulation, which contributes to the available supply for harvesting and the potential for future growth. There are several global maps of above-ground biomass (AGB) available that we can use in the model including:

a) NASA Global Aboveground and Belowground Biomass - these maps show wood biomass carbon density at 300m resolution for 2010. This data has undergone validation [11]. The Africa portion of the dataset is derived from ALOS PALSAR data [12]. The data show moderately good agreement with LiDAR-based observations (84% correlation) and with field data from 144 plots [12]. However, the NASA dataset may underestimate standing biomass in semi-arid open-canopy landscapes.[5]

b) World Conservation Monitoring Centre - this map shows above- and below-ground wood carbon stocks in tons per hectare for ~2010. The resolution is ~300m and the data has not undergone any validation.

c) Woodwell Climate Research Center (formerly Woods Hole Research Center) - this map shows woody biomass density for tropical countries at 500m resolution for ~2012.

d) GFW Live Woody AGB Density - this map shows aboveground wood biomass at ~30m resolution for the year 2000 but only applies to areas with non-zero tree canopy cover (so many trees outside forests may be unaccounted for).

e) GlobBiomass - this map shows above ground wood biomass expressed in oven-dry tons per hectare at 100-150m resolution for 2010

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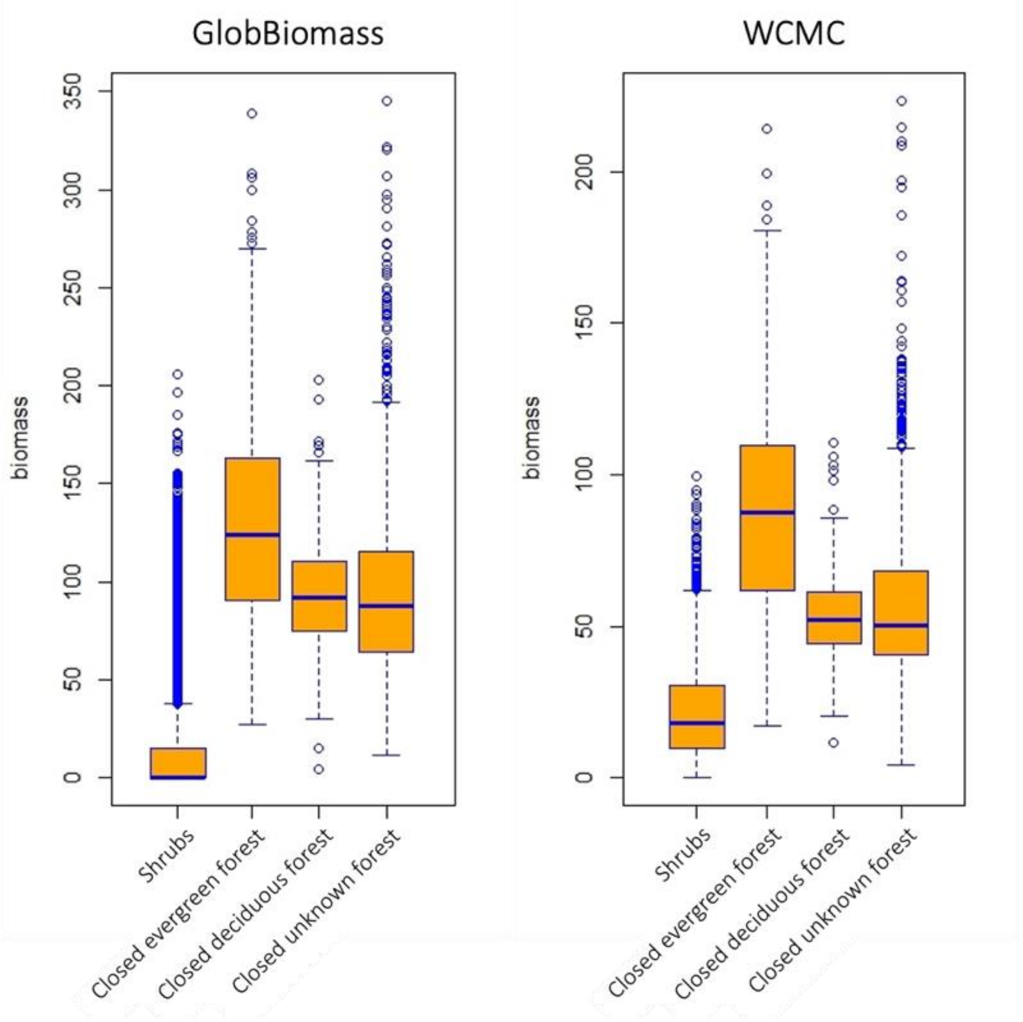
[5] Note this error would result in an upward bias in fNRB estimates.

24. Note these datasets are all 10 or more years old. While this may miss some of the changes that have occurred in the last decade, this is useful for our approach because we typically begin our simulations using a base year ~10 years in the past and calibrate our models to observed changes that occurred over leading up to 2010.

25. The maps vary in year and uncertainty, as well as the heterogeneity of data quality (e.g. some maps have been well-validated in moist tropical regions but have greater uncertainty in dry forest regions). The choice of map will lead to different values of initial biomass stock, which can vary across different land cover types and sub-national administrative areas. **Figure 1** shows the distribution of biomass in Kenyan shrublands and forests from two of the data sources: WCMC and GlobBiomass.

Figure 1: Box-and-whisker plot showing the distribution of AGB stocks in measured in tons of dry matter per hectare 2010 in common Kenyan land cover types from two biomass maps (the dark line shows the median of biomass density, the upper and lower edges of the box show the first and third quartile, the upper and lower "whiskers" show the minimum and maximum values, and circles show statistical outliers).



26. Land cover categories are taken from a vector dataset of land cover types that we layered with the biomass raster data (note, that the vertical axes differ in magnitude). The distributions show differences. In GlobBiomass, the median biomass density in shrubland is zero but ranges as high as 200 t/ha. In contrast, the median biomass in WCMC's data is ~20 t/ha and only ranges up to 100 t/ha.

27. For this assessment we use the NASA dataset for several reasons:

    a) The data is from 2010, which coincides with our base year

    b) The coverage extends beyond tropical regions and includes biomass of non-dominant land cover types within each pixel

    c) The dataset has undergone validation and includes pixel-level uncertainty estimates

28. In addition, while concerns about uncertainty introduced by the selection of one biomass map over another are warranted, we accommodate this uncertainty by running Monte Carlo simulations. These simulations yield a distribution of fNRB values based on the variability of key input parameters (described in detail below).

2.6 Biomass growth functions

29. These functions rely on two important parameters: annual growth rate and maximum stock within each pixel.[6] We use the following logistic (sigmoidal) growth function to simulate woody biomass growth in each pixel and land-cover type:

$$AGB_{(t+1)i,j} = AGB_{(t)i,j} + AGB_{(t)i,j} \cdot r_{max,j} \cdot \left(1 - \frac{AGB_{(t)i,j}}{K_j}\right)$$

Where:

- *i* and *j* are indices for pixel i in land cover type j
- $ABG_{(t)i,j}$ or $ABG_{(t+1)i,j}$ aboveground wood biomass in pixel *i* and land cover *j* at time t or t+1
- $r_{max,j}$ is the slope at the inflection point of the sigmoidal growth function, which determines the maximum growth rate of woody biomass in each land-cover type *j* [7]
- K_j is the maximum woody biomass in land-cover type *j* (or “carrying capacity”)

30. The growth function we use is a generic logistic function that simulates tree growth under competition: growth starts slowly, accelerates, and then slows again as trees crowd each other out until stocks reach a maximum. Simulation outcomes are sensitive to both r_{max} and K. For r_{max}, we use growth rates from the IPCC’s 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [13]. The IPCC guidelines provide region-specific woody biomass growth rates for different global ecological zones (GEZ) [14] and land-use land cover (LULC) categories [15]. Data are provided across three age categories: “< 20 years after disturbance or establishment”, “> 20 years after disturbance or establishment”, and “primary” or mature stands. We select values of r_{max} that result in the slope at the inflection point of the sigmoidal growth function to align more “< 20 years after disturbance or establishment”, which are the most appropriate values to simulate the maximum growth rate, which occurs at the inflection point of the growth function (**Table 1**).

31. Our maximum biomass stock estimates “K” are derived from the NASA Global Aboveground and Belowground Biomass dataset described above. To obtain a reasonable estimate of the maximum potential woody biomass stocks in each region/GEZ/LULC category while avoiding outliers, we mapped the NASA data by regions, GEZ, and LULC category and ran zonal statistics to obtain the mean values of points falling within the top decile. **Table 1** shows the values we derived of both r_{max} and K for each GEZ and LULC category in the Africa region.

32. Both r_{max} and K are sources of uncertainty in biomass supply. To accommodate this uncertainty, we use variation in both parameters (defined by standard deviations shown in **Table 1**) to run Monte Carlo simulations. This process is discussed in more detail below.

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[6] Pixel size can vary, but models are generally limited by the lowest resolution input file. For our regional or global model, we use 1km x 1km pixels. However, for sub-national or project-scale models we could use higher resolutions like 100m or 30m.

[7] Note, r_{max} is not a direct estimate of the maximum growth rate. Rather, it is a parameter proportional to the maximum growth rate such that maximum growth equals the product [¼ r_{max} K]. Applying this to the top row in Table 1 yields a maximum growth rate of ~3.8 oven-dry tons per hectare per year.

33. In addition, MoFuSS can simulate future tree cover loss that might be caused by drivers unrelated to woodfuel demand, such as agricultural expansion, but we do not predict future degradation. In areas that are not affected by future tree loss, the simulation allows trees to grow to their full potential unless they are affected by woodfuel harvesting. We base fNRB in part on that growth potential. However, those regions may be affected by factors that contribute to degradation, such as grazing, smallholder farming, low-intensity selective logging, altered fire regimes, pests, genetic erosion, topsoil sterilization, among others, and reduce tree growth even in the absence of woodfuel demand. In that case, those regions will never reach K_j.

Table 1: A selection of values of K and rmax and standard deviations used in the global model

GEZ and MODIS land cover category	r_{max}	r_{max} st dev	K	K st dev
SSA_Tropical dry forest_Evergreen Needleleaf Forests	0.18	0.16	85	3
SSA_Tropical dry forest_Evergreen Broadleaf Forests	0.07	0.06	216	12
SSA_Tropical dry forest_Deciduous Broadleaf Forests	0.15	0.13	105	26
SSA_Tropical dry forest_Mixed Forests	0.13	0.12	117	12
SSA_Tropical dry forest_Closed Shrublands	0.24	0.22	65	7
SSA_Tropical dry forest_Open Shrublands	0.22	0.2	70	7
SSA_Tropical dry forest_Woody Savannas	0.12	0.1	134	25
SSA_Tropical dry forest_Savannas	0.2	0.18	77	9
SSA_Tropical dry forest_Grasslands	0.25	0.23	62	7
SSA_Tropical dry forest_Permanent Wetlands	0.13	0.12	119	25
SSA_Tropical dry forest_Croplands	0.31	0.27	51	7
SSA_Tropical dry forest_Cropland/Natural Vegetation Mosaics	0.31	0.27	51	7
SSA_Tropical shrubland_Evergreen Broadleaf Forests	0.02	0.02	148	18
SSA_Tropical shrubland_Deciduous Broadleaf Forests	0.02	0.02	169	12
SSA_Tropical shrubland_Mixed Forests	0.03	0.02	141	17
SSA_Tropical shrubland_Closed Shrublands	0.04	0.04	81	5
SSA_Tropical shrubland_Open Shrublands	0.06	0.05	59	11
SSA_Tropical shrubland_Woody Savannas	0.03	0.02	132	12
SSA_Tropical shrubland_Savannas	0.04	0.04	91	18
SSA_Tropical shrubland_Grasslands	0.05	0.05	71	7
SSA_Tropical shrubland_Permanent Wetlands	0.03	0.03	110	15
SSA_Tropical shrubland_Croplands	0.07	0.06	54	8
SSA_Tropical shrubland_Cropland/Natural Vegetation Mosaics	0.17	0.15	21	7

2.6 Accounting for other carbon pools

34. MoFuSS focuses on stocks and growth rates of AGB, the main carbon pool on which woodfuel users depend. However, other pools of terrestrial carbon like soil organic carbon (SOC) and dead organic matter (DOM) may be affected by woodfuel harvesting, particularly if harvesting leads to forest degradation or deforestation. The current version of MoFuSS does not account for changes in SOC and only addresses DOM indirectly, as explained below.

2.6.1 SOC

35. MoFuSS cannot accommodate SOC. While there are global maps of SOC, these are snapshots and do not demonstrate changes over time [16]. Changes in SOC resulting from woodfuel harvesting are not well documented and are beyond the scope of the model. In addition, to our knowledge, changes in SOC have not been identified as a major source of concern about inaccuracies in assessing emission reductions from woodfuel-based carbon offset projects.

2.6.2 DOM

36. DOM consists of two sub-pools of organic matter: dead wood and leaf litter. We treat leaf litter in the same way as SOC; we acknowledge that pools of leaf litter may be affected by woodfuel harvesting, but estimating these changes is beyond the scope of the model. In contrast, dead wood forms a source of fuelwood, and reliance on deadwood could relieve pressure from standing stocks of living trees. However, accounting for the use of deadwood in the regional model is difficult for several reasons:

a) There is no guidance from the IPCC. The Tier 1 recommendation from the 2006 edition of the IPCC's "Good Practice Guidelines" is to assume that "dead wood and litter carbon stocks are in equilibrium" [17 p. 4.20]. While it's not clear if the assumption of equilibrium applies to areas where people harvest woodfuel, it is likely valid for a "first-order" approximation. Most of the areas from which people harvest woodfuel are continually harvested. While our modeling period includes a starting year, woodfuel consumption predates our simulations. It's unlikely that large stocks of deadwood accumulated during one year, affecting the way people harvest from living trees in subsequent years. An exception would be newly cleared land, which we can address (see Comment 3 below).

b) Including deadwood as a distinct source of supply would be very difficult without extensive data collection that is beyond the scope of this study. There are no default values readily available. Table 2.2 from the IPCC's 2006 Guidelines includes default values for litter, but the section of the table for deadwood is filled with "n.a." for "not available" across all forest types. The IPCC's 2019 "Refinement" provides no new information [18].

c) MoFuSS has an optional module that can accommodate pulses of dead wood that occur as a result of land clearance. When that option is used, a fraction of the woody biomass that is cleared is available for woodfuel consumers in the subsequent year. However, the land clearance option relies on past patterns of land cover change to predict future tree clearance. This predictive algorithm does not work well for multi-country models because there is too much variation in factors driving tree loss. Therefore, the module was not used in this assessment.

2.7 Biomass consumption

37. Both current and future biomass consumption are contributors to fNRB. Spatially modeling the impacts of biomass consumption requires estimates of the quantity consumed and the location of consumers. To estimate the quantity of wood and charcoal consumed, we rely on two simple parameters: the number of users and the amount per user. The number of wood and charcoal users is based on WHO's recently updated "Global Household Energy Model", which projects the number and percentage of

people using primary household cooking fuels in rural and urban areas of low- and middle-income countries.[8] By not accounting for stacking, we may be introducing uncertainty in woodfuel demand. However, it is unclear whether this leads to underestimates or overestimates. For example, a fraction of the people counted as "primary charcoal users" may actually cook some of their meals with LPG or fuelwood and use less charcoal than people counted as "primary charcoal users" who do not stack with other fuels. In that case, we could be overestimating charcoal consumption. By the same token, a fraction of the people counted as "primary LPG users" may cook with some of their meals with charcoal and use less LPG than people counted as "primary LPG users" who do not stack with other fuels. This could lead to an underestimation of charcoal consumption. The same applies to other categories of primary fuel users. There is very little reliable data on fuel consumption among fuel-stacking households. We would need to do detailed country-specific research to understand this better, which was beyond the scope of this study.

38. Figure 2 shows WHO projections for four African countries through 2050. Note the combined number of wood and charcoal users in Kenya and Ethiopia is projected to peak before 2040, while consumption in Nigeria and Malawi is projected to increase. We use these national projections disaggregated by rural and urban regions for each country in the analysis.

2.8 Residential, commercial, and industrial woodfuel consumption

39. The MoFuSS model focuses primarily on residential woodfuel demand. In some countries, there may be industrial or commercial use of wood that affects tree cover. In earlier versions of MoFuSS, we omitted that data because of a lack of reliable data that would allow us to map demand in the same way that we map residential demand (described below). However, in response to public comments, we attempt to account for non-residential woodfuel demand from commercial entities like hotels and restaurants, public institutions like schools, prisons, and military barracks, and cottage industries like brick burning, ceramics, beer brewing, and fish smoking among others. To include these sources of demand, we did a limited literature review focused on sub-Saharan Africa.[9] The results of this review are shown in **Table 2**.

Table 2: Non-residential woodfuel consumption reported in four studies from East African countries

Country – year [ref]	Units	Rwanda - 2019 [19]		Uganda - 2020 [20][b]		Kenya - 2000 [21][c]		Kenya - 2018 [22][d]	
Fuel		Wood	Charcoal	Wood	Charcoal	Wood	Charcoal	Wood	Charcoal
Public institutions [a]	Mton	0.7	0.0					1.3	0.1
Restaurants / food vendors	Mton	0.1	0.2			1.3	0.4		
Tea drying	Mton	0.016				0.2			
Tobacco curing	Mton					0.1			
Brickmaking	Mton	0.22				0.1			
Other industry	Mton					0.2			

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[8] Urban woodfuel users rely primarily on commercially supplied fuelwood and charcoal, which is usually transported by road from distant rural areas. Rural users generally gather wood from nearby. These different harvesting practices result in different geographic patterns of impacts, which we model using different algorithms.

[9] This project did not include sufficient time or budget to collect data from all regions.

Total non-residential	Mton	1.0	0.2	0.5	0.3	1.8	0.4	1.3	0.1
Residential	Mton	6.0	0.3	15.2	2.4	15.9	2.3	9.6	2.0
Non-residential as pct of residential	%	17%	59%	3.3%	11%	14%	3%	11%	19%

Table notes:

a. Public institutions include schools, restaurants, prisons, military barracks, and health clinics.

b. The analysis from Uganda includes tea factories, soap making, beverage preparation, sugar, bakeries, and brick making. Industries include tea factories, soap industries, beverage industries, sugar industries, bakeries, and brickmaking. However, the report does not disaggregate wood consumption by industry.

c. “Other industry” from Kenya’s 2000 survey includes dairy, jaggary, and fish smoking. This study did not include public institutions.

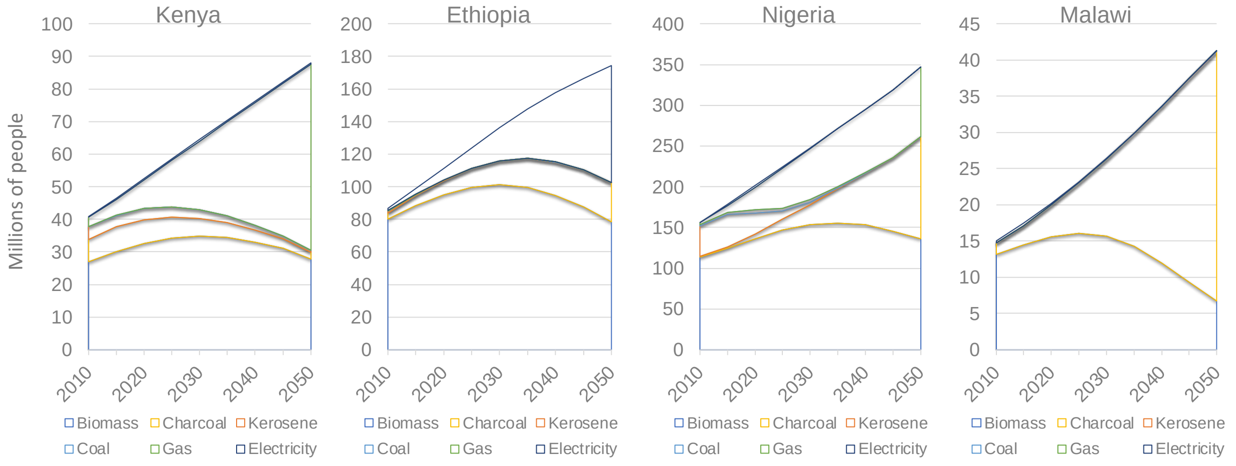
d. This report did not include commercial or industrial woodfuel consumption - only public institutions.

40. From **Table 2**, it is apparent that non-residential woodfuel consumption is small but significant in the four countries that were reviewed. While these four studies are not generalizable to other countries and regions, in the absence of additional data, we use the results as general guidelines to adjust woodfuel consumption throughout the assessment. To do so, we create fuelwood and charcoal multipliers of 1.1 and 1.2 respectively, effectively increasing modeled fuelwood demand by 10% and charcoal demand by 20% to account for non-residential uses. When carrying out detailed, country-specific studies, these multipliers can be adjusted based on data obtained from sources within each country.

2.9 Accounting for non-energy wood demand and timber plantations

41. In addition to non-residential energy consumption, all countries consume wood for non-energy applications like building materials and timber exports. Much of the supply of this form of industrial wood originates from plantations, which are often managed sustainably. Moreover, plantations are generally inaccessible to woodfuel consumers, so they do not form a part of the supply-demand dynamic that we are modeling.

Figure 2: Estimated population of primary cooking fuel users for a selection of African countries from WHO’s Global HH Energy Model (2010-2050) [23,24]



42. Nevertheless, this raises questions about how MoFuSS should treat tree plantations in assessing biomass supply. If industrial plantations are effectively off-limits to woodfuel consumers, then they could arguably be made more difficult to access, in the same way that MoFuSS makes protected areas difficult to access. However, unlike protected areas, we do not have accurate maps of forest plantations for most countries. There is a recent database of tree plantations, but it has very limited coverage in sub-Saharan Africa [25]. Therefore, the regional MoFuSS model does not account for forest plantations. This may raise some concerns about inaccuracies; however, any inaccuracies as a result of ignoring plantations are likely minimal. For example, South Africa, which has a very mature forestry industry, has a little over 2 million hectares of forest plantations, which is less than two percent of the country's total land area [25].

2.11 Quantifying household woodfuel consumption

43. To estimate the quantity of fuelwood and charcoal consumed, we relied on a mix of CDM default values and regionalized estimates from existing project documents, which were cross-referenced with data from household surveys and field measurements.

44. For fuelwood, CDM recommends a default of 400 kg (wet) per person per year for carbon offset methodologies [26]. Our analysis expresses woody biomass in oven-dry terms. Cut, air-dried wood varies in moisture content, but it is reasonable to assume that air-dried fuelwood has a 20% moisture content (measured on a wet basis)[10]. Thus, the CDM's default value of 400 kg (wet) represents about 320 kg of oven-dry wood per person. This is lower than most data suggest. For example, a review of baseline wood consumption in CDM projects claimed in Project Design Documents (PDDs) conducted by CDM indicates that registered projects observe higher consumption in most regions, particularly in Latin America (**Table 3** – middle columns). Estimating consumption based on global datasets also results in higher per capita fuelwood use than the CDM default (**Table 3** - right column).

Table 3: Average annual consumption of woody biomass per person

Region	N	Annual per capita consumption (kg)		Regional average of UN and DHS data (kg)
		PDD value*	PDD adjusted to oven-dry weight	
Sub-Saharan Africa	58	0.87	0.70	0.59
Latin America	6	1.11	0.89	1.10
East Asia	10	0.95	0.76	0.44
South Asia	35	0.4	0.32	0.57
Total	109	0.74	0.59	0.62

* Assuming the PDD value is given as "air-dry" wood

45. Similarly, data from Kitchen Performance Tests submitted to this team by project developers also indicates that annual wood consumption exceeds 400 kg per year in most project settings. In acknowledgment of these disparities, the team adjusted wood consumption upwards. Regional values are given in **Table 4**.

46. Charcoal consumption is estimated by assuming households consume a similar quantity of "useful energy" as those households that use fuelwood. This is a simple calculation using calorific values and

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[10] Wood moisture can be expressed on a wet- or dry-basis [see Section 5.1 of reference 27 for a full explanation].

stove efficiencies of both fuelwood and charcoal.[11] Regional charcoal consumption values are also given in **Table 4**. These estimates also align with data provided by project developers.

Table 4: Regional per capita wood and charcoal consumption used for this assessment

Region	Fuelwood (oven-dry tons/person-year)	Charcoal (tons/person-year)
Sub-Saharan Africa	0.40	0.16
Latin America	1.10	0.18
East Asia	0.44	0.16
South Asia	0.40	0.25
Other regions	0.62	0.16

47. To simulate the impacts of charcoal consumption in MoFuSS, we need to account for the wood that is required to produce charcoal. To do this, we multiply the consumption from **Table 4** by a conversion factor. We use the FAO default of 6 units of wood per unit of charcoal [28].[12]

48. The location of biomass users is also an important determinant of impacts. For example, people close to an abundant source of wood will have a lower impact than people for whom nearby wood is scarce. To estimate the location of woodfuel users, we developed the following three-step process:

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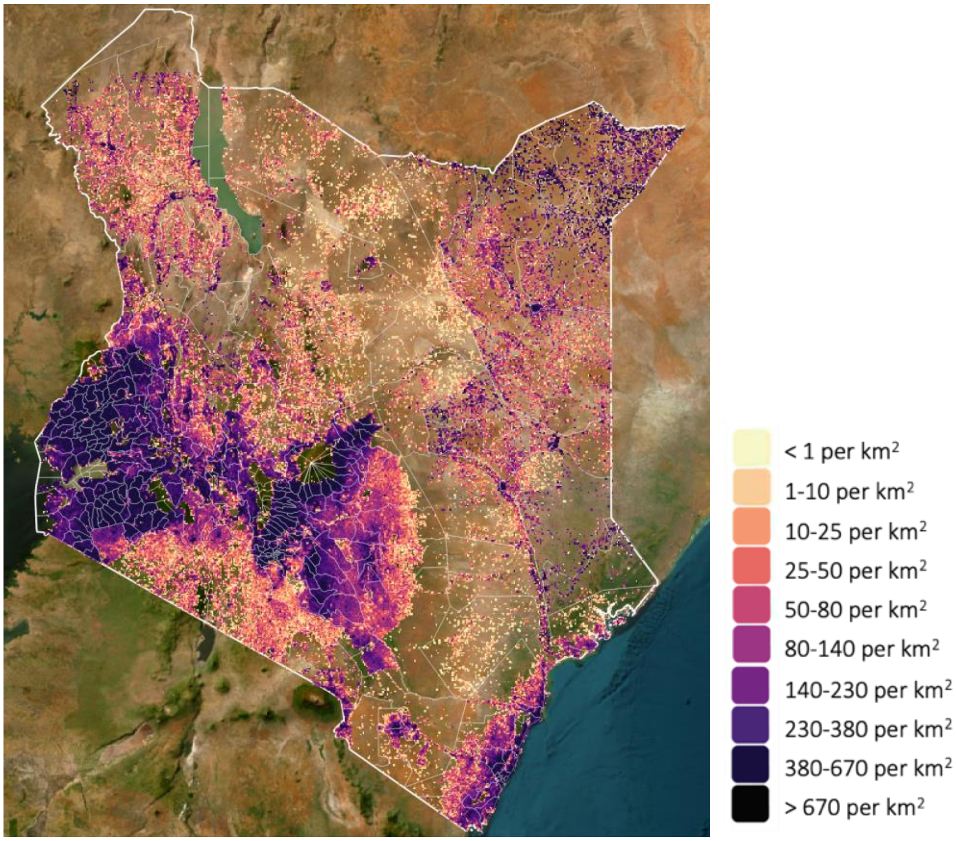
[11] These conversions assume wood stoves are 15% efficient, oven-dry wood has a calorific value of 18 MJ/kg, charcoal stoves are 25% efficient, and charcoal has a calorific value of 27 MJ/kg.

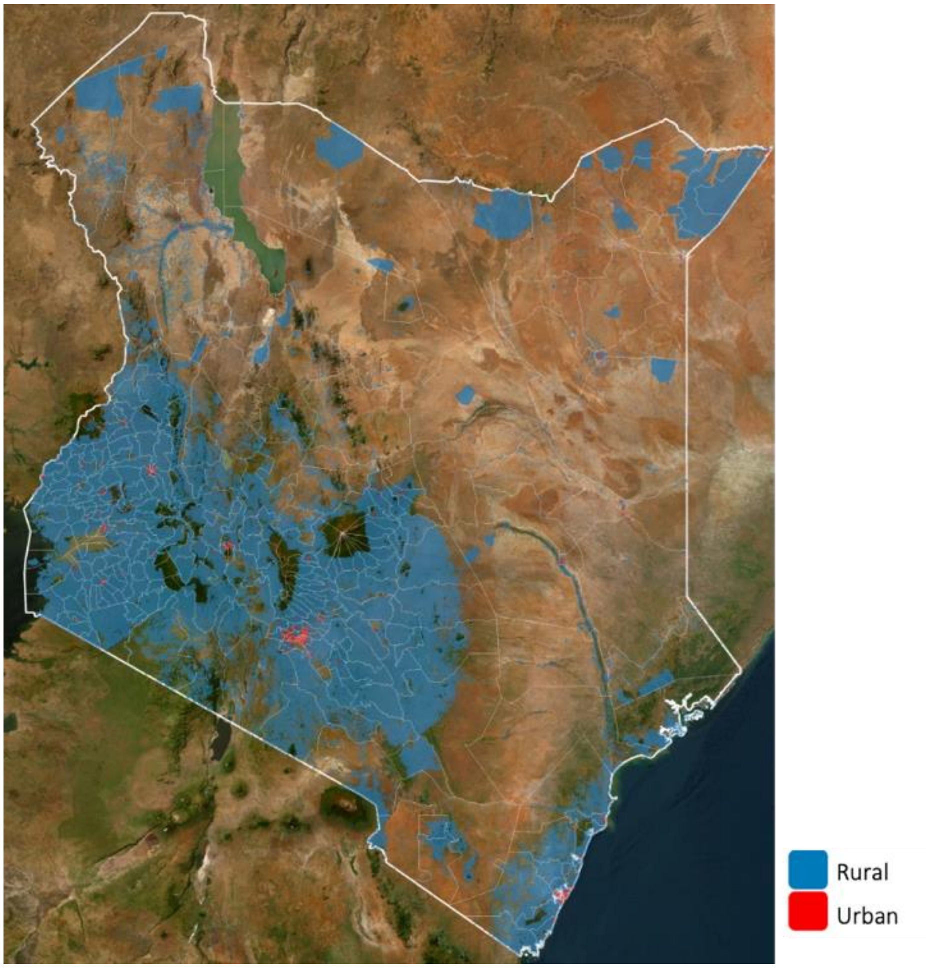
[12] The CDM default wood to charcoal conversion ratio was recently changed from 6:1 to 4:1 [26]; however we feel that the new value is too conservative and not supported by data. For a review of charcoal conversion efficiency in traditional kilns, see [29].

Figure 3: WorldPop map showing population density deciles in Kenya



a) **Step 1: Obtain spatial population distribution data.** For this, we use population density maps published by WorldPop, which has recent, freely available, high-resolution data for all countries included in this study. **Figure 3** shows an example of WorldPop data from Kenya.

Figure 4: Rural and urban populations in Kenya based on population density from WorldPop



b) **Step 2. Map fuel use among the population.** For this, we use the WHO's projections of populations using different primary cooking fuels, disaggregated by urban and rural sub-populations. However, WorldPop's spatial data doesn't differentiate between urban and rural areas. To make this distinction, we define urban and rural areas by ranking all pixels from the WorldPop map by population density in descending order and defining a cutoff such that the cumulative sum of pixels in descending order equals UNDESA's estimate of the country's urban population in that base year [30]. The pixels that add to the urban cut-off are defined as urban and the remaining pixels are defined as rural. **Figure 4** shows the results of applying this step to Kenya. Note, that this process introduces a risk of classifying very high-density rural areas as urban but this is unlikely to have a large impact on the results of the analysis. In addition, for MoFuSS simulations, we assume that urban and rural areas remain fixed in space, but populations grow through the simulation period according to UNDESA projections [30].[13]

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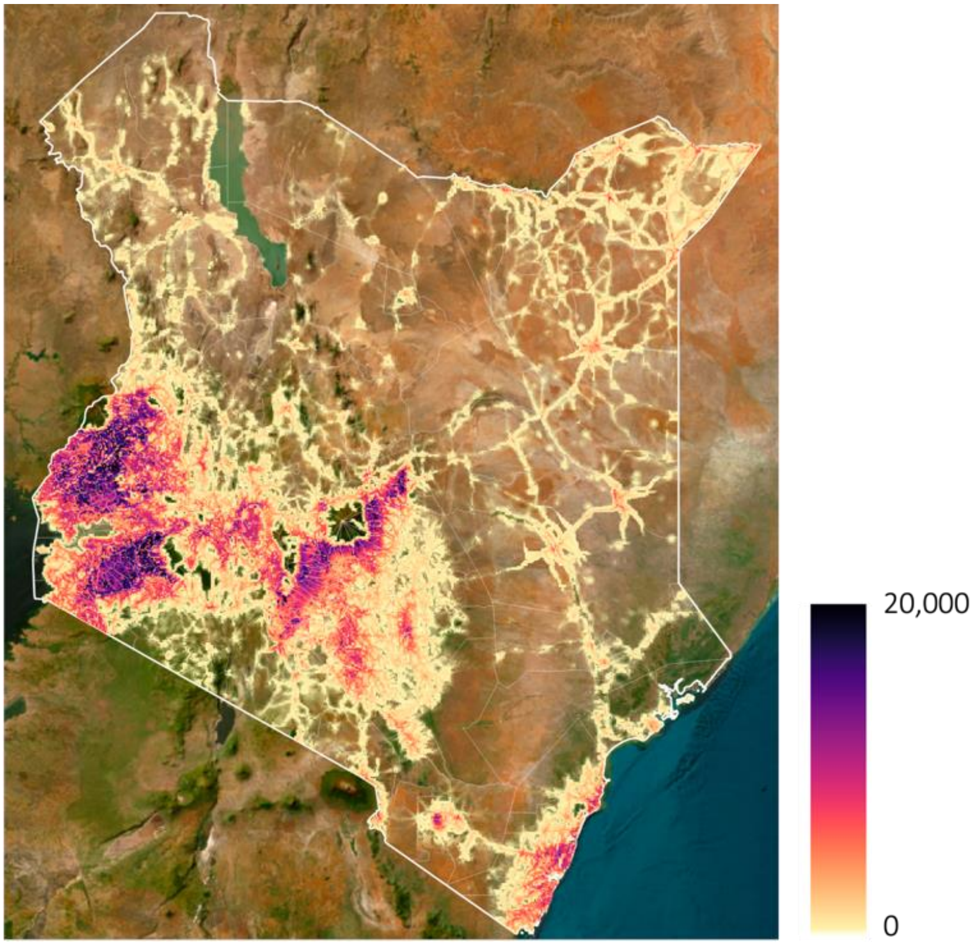
[13] This assumption is not necessarily accurate, but it is beyond the scope of this model to predict how urban areas will change and grow over a 20- or 30-year period.

c) **Step 3**. **Create a map of wood and charcoal demand.** Using the urban and rural population maps defined in the previous step, we use WHO's estimates of urban and rural fuel use to distribute wood and charcoal demand throughout each country. **Figure 5** shows a map of cumulative woodfuel consumption between 2010 and 2050 for Kenya.

Figure 5: Woodfuel consumption between 2010 and 2050 measured in tons per km^2



2.12 Spatializing biomass harvesting

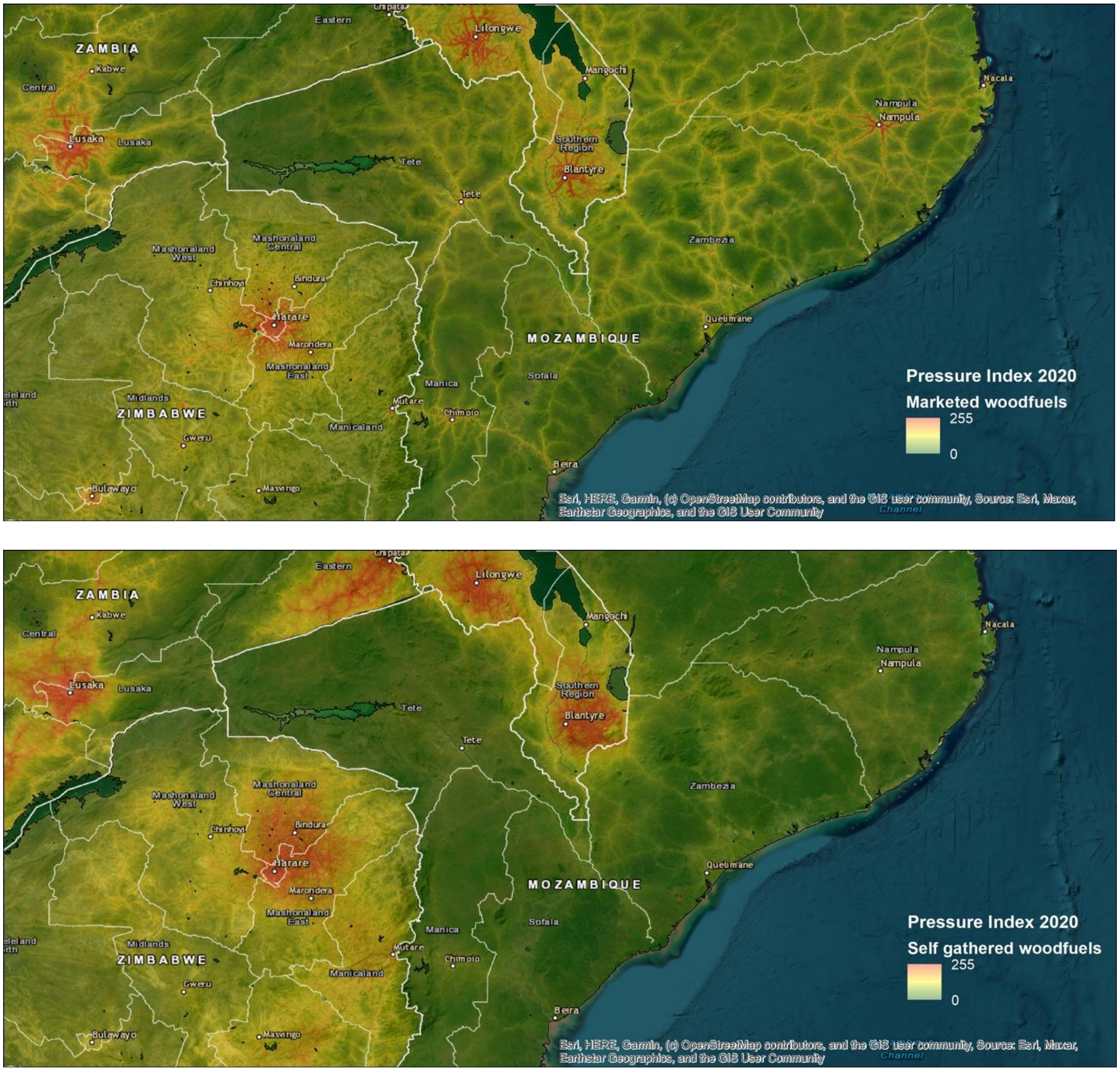
49. In the previous section, we described how biomass consumption scenarios were produced by integrating several datasets. However, these results show where biomass is actually used, but not necessarily harvested. Both WISDOM and previous versions of MoFuSS use some sort of accessibility analysis whose description is beyond the current report [9]. However, there are two key innovations in this version of MoFuSS:

2.12.1 Pressure maps

50. Pressure maps show the likelihood of wood harvest across the landscape based on demand and accessibility in populated areas. This analysis accounted for wood and charcoal demand across millions

of populated pixels spread throughout the world. **Figure 6** shows this for a region of Southern Africa. The top part of **Figure 6** shows pressure from commercially traded fuelwood and charcoal, and the bottom shows pressure from demand for fuelwood collected by rural households for their own use. Commercial supply is dependent on roads, which is clear from the upper map. In contrast, subsistence collection is more diffuse and not as reliant on road networks. Using MoFuSS, we calculated pressure maps for all populated points, which we use to create maps of biomass harvesting over the continent. The underlying code that generates pressure maps is available on GitHub. For a detailed description of how the pressure maps are created see Ghilardi et al. 2016 [9].

Figure 6: Pressure map to seed biomass harvesting locations to meet demand for charcoal and commercially traded fuelwood (top) and fuelwood collected by rural households (bottom).



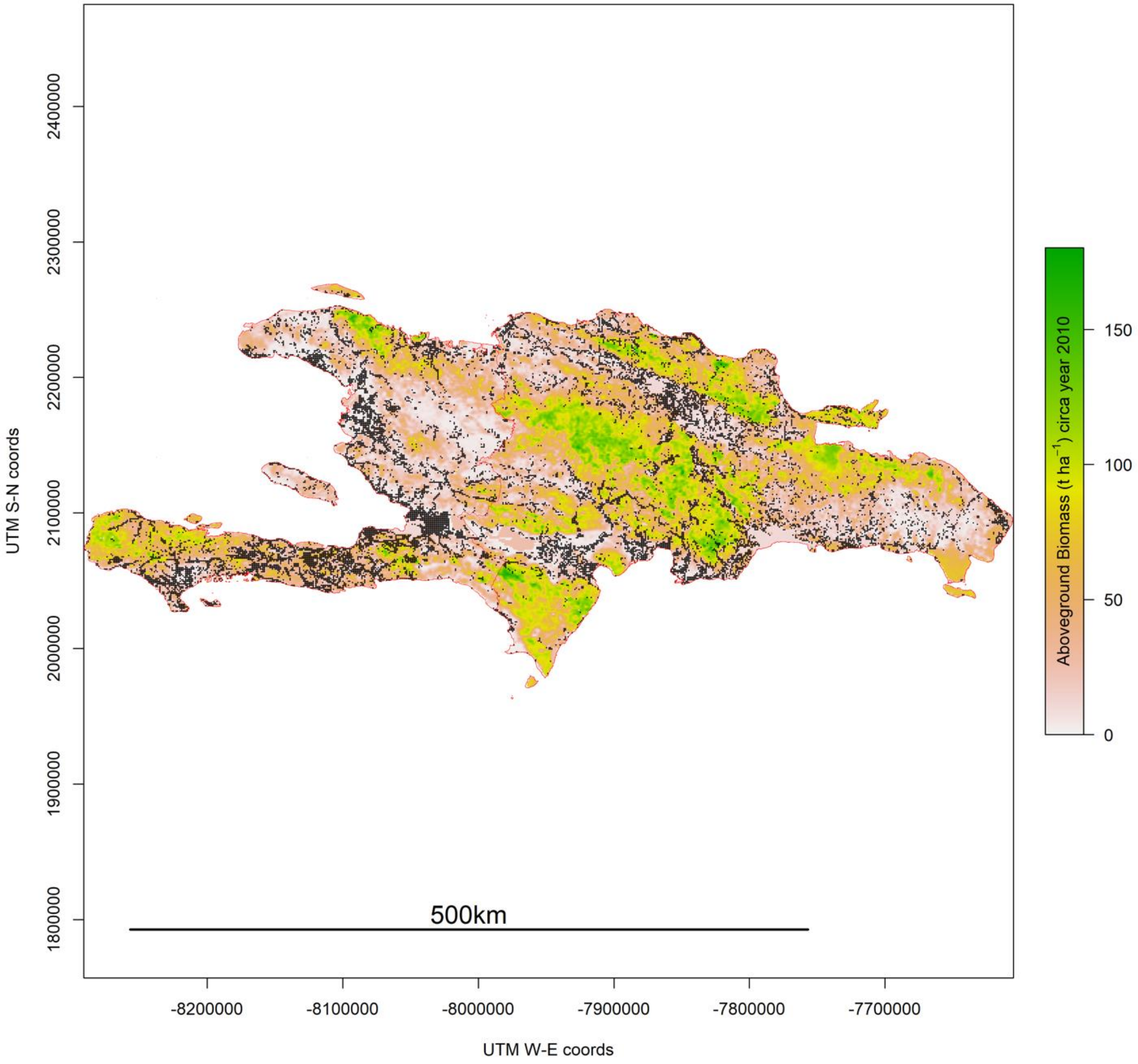
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

2.12.2 Annual reassessments

51. Pressure maps are dependent on demand. Our simulations account for population growth, urbanization, and "business-as-usual" shifts in fuel choice over time, as forecast by WHO [23], which result in changes in demand for both collected and marketed woodfuels. To accommodate these changes, we generated hundreds of millions of accessibility maps needed to account for changing population distribution using self-collected and commercial woodfuels across all world regions between 2010 and 2030. This was accomplished by developing novel code in C++ and using high-performance computing. Figure 7 shows populated places in Haiti and the Dominican Republic. Each dark point represents a 1 km pixel with people. The map of populated places is overlain on NASA's AGB map for the two countries.

Figure 7: Populated places in Haiti and the Dominican Republic overlain on an AGB map for both countries



2.13 The relationship between woodfuel consumption and fNRB

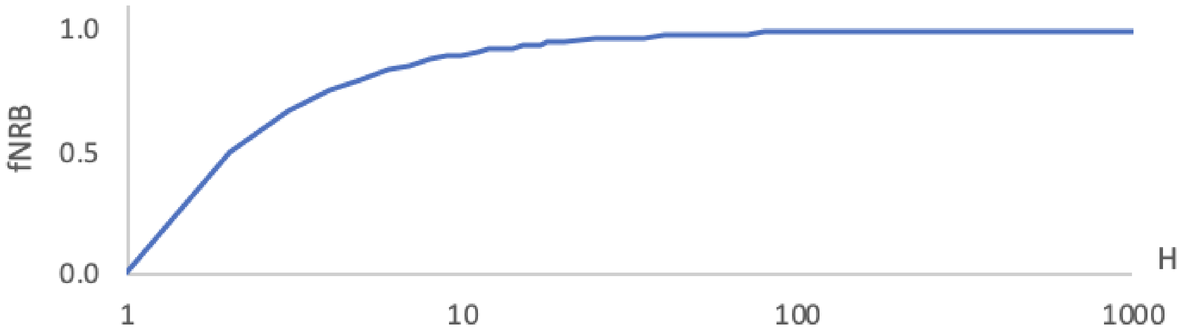
2.13.1 Tool30

52. Under the TOOL30[14] methodology, fNRB increases with consumption. For example, if we combine Equations 1 and 2 from TOOL30, then for a given land cover category, we get:

$$fNRB = \left(1 - \frac{RB}{H}\right) = \left(1 - \frac{MAI}{H}\right) \qquad \text{Eq. 1}$$

53. This results in a relationship like the plot in **Figure 8** (note the x-axis is logarithmic).

Figure 8: fNRB as a function of H (with H expressed as a % of MAI)



54. However, in reality, MAI is not a constant. Rather it varies over time and with standing stock [31]. MAI is affected by harvesting and can actually increase after a harvest event as a result of reduced competition for light and nutrients. MoFuSS avoids using MAI and uses growth curves as explained above. However, this makes it difficult to predict how the model responds to different harvest regimes because the response depends on the growth function parameters discussed in the previous sections.

2.14 Calculating fNRB

55. There are multiple ways to use the changes in biomass simulated by MoFuSS to estimate fNRB. In this assessment, we estimate fNRB within a given administrative boundary by identifying pixels within the boundary that experience biomass losses during a specific timespan. This wood loss is defined as non-renewable biomass or NRB. To estimate fNRB, we sum the losses occurring within the administrative boundary of interest and divide that by the total biomass harvest within that same boundary. Please refer to the supplementary material of Ghilardi et al 2016[15] [9] for a detailed description of how harvest events and natural regrowth of woody biomass interact in MoFuSS over space and time to render pixel-based results of NRB.

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[14] https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-30-v4.0.pdf/history_view

[15] https://docs.google.com/document/d/140duZZaBIUuCG7nvgHwsdw7Wkm2Nce7cenEpEHEvgqI/edit

2.15 Biomass harvest and NRB in MoFuSS

56. The spatial distribution of fuelwood harvesting and collecting sites is determined in part by their proximity to demand centers, or places where woodfuels are actually used. The seeding of harvesting sites during any time step is based on pressure maps, a stochastic component, and overall fuelwood demand in populated areas, which, in this study, are represented by 3.3 million villages, towns, and cities across sub-Saharan Africa, Latin America and Asia.

57. The overall woodfuel demand for each time step is distributed in space as harvest events following equation 2:

$$pfw_{(t)j,k} = Px_{(t)j,k} * \frac{\sum_{i} C_{ik} - df_k}{\sum_{j} Px_{jk}}_{(t)} \qquad \text{Eq. 2}$$

Where:

$pfw_{(t)j,k}$ is the expected amount of fuelwood harvested (in tons of dry matter) in pixel *"j"* during time period "t"; k is an index of fuelwood harvesters; MoFuSS accounts for two types of harvesting: self-collection of fuelwood and commercial harvesting of both marketed fuelwood and wood used to make charcoal.

$Px_{(t)k}$ is the pressure index from the "inverse distance weight" or IDW algorithm [see 9] over pixels affected by harvesting events during time step *"t"* by collectors "k".

C is woodfuel consumption (in tons of dry matter) within each locality, village, or city "*i*"

df is the overall amount of fuelwood in the study area available as a by-product of deforestation events driven by factors agricultural expansion or other factors.

58. In the model, each time step is one iteration (one year in this analysis) and n-steps constitutes a simulation. MoFuSS runs for any specified simulation period times the number of Monte Carlo runs that are set, producing three main output parameters: a) the remaining AGB stock (growth minus harvest at t = n), b) NRB calculated in pixels where decreases in AGB have occurred (Eq. 3), and c) fNRB, calculated as the fraction of total fuelwood consumption that is non-renewable. These three basic outputs are modeled: 1) within each iteration (mimicking a static supply-demand analysis); 2) within each simulation period; and 3) for the entire set of Monte Carlo realizations for NRB and fNRB.

$$NRB_{t=n,j} = \begin{cases} 0 \; if \; AGB_{t=n,j} \geq AGB_{t=0,j} \\ AGB_{t=n,j} - AGB_{t=0,j} \; if \; AGB_{t=n,j} < AGB_{t=0,j} \end{cases} \qquad \text{Eq. 3}$$

59. Where NRB(t=n) is the amount of wood harvested from pixel "j" that results in a net decrease in AGB between time t = 0 and t = n (expressed in tons of dry matter). In this study, n may correspond to the 40 year period between 2010 and 2050, or it can be sub-divided into other time increments (e.g. 2020-2030, 2030-2040, etc). Each Monte Carlo realization generates a different value of NRB(t=n) by repeating Eq. (3) in each run. NRB(t=n) is calculated at the pixel-level, meaning that it does not account for any increment of AGB occurring in areas where AGB(t=n) ≥ AGB(t=0). In other words, NRB(t=n) is not the net decrease of AGB over the accessible area. Instead, it accounts for losses of AGB only in the set of pixels where a loss occurred.

60. Finally, the fNRB, the ratio of NRB to wood harvested is calculated as in Equation 4:

$$fNRB_{(t=n),j} = \frac{NRB_{(t=n),j}}{H_j} \qquad \text{Eq. 4}$$

Where Hj is the sum of woody biomass harvest between year 1 and n in pixel “j”.

61. It is important to stress that to apply fNRB in projects or programmes of activity, fNRB must be aggregated from pixel-based values to a geographic area that is appropriate for the scale of the intervention, which may be national or sub-national. To do this, the model aggregates NRB from each pixel within a project boundary or administrative area and divides that by total consumption during the same time period within the same boundary. This calculation is shown in Equation 5:

$$fNRB_{(t=n),project\ area} = \sum_j NRB_{(t=n),j} / \sum_j H_j \qquad \text{Eq. 5}$$

62. Where “j” is a pixel in the “project area” and “project area” is shorthand for a country, sub-national administrative boundary, or any project-specific geographic boundary. However, the boundary should be selected such that the area includes all likely harvest areas used by the target woodfuel consuming population.

2.15.1 Use of deforestation by-products

63. Most countries included in this analysis experience some annual loss of tree cover, which may contribute to long-term deforestation. These losses are identified by tracking annual changes in canopy cover using remotely sensed data [32]. Tree removals identified by remotely-sensed changes in canopy cover are typically caused by land clearance for large-and small-scale agricultural expansion rather than woodfuel harvesting [33]. However, in some situations, the by-products of land clearance are used for firewood or charcoal production [29,34]. When this occurs, the harvested biomass is non-renewable because land-clearance for agriculture makes it difficult for trees to regenerate; however, the biomass does not contribute to (f)NRB because the trees would have been removed regardless of woodfuel demand. Thus some fraction of demand might be satisfied with non-renewable biomass that does not contribute to fNRB. The MoFuSS model includes an optional module that simulates these processes and adjusts fNRB results accordingly. However, for this assessment study we did not use this feature off due to a variety of reasons, which are explained in the Technical Appendices below.

2.15.2 Treatment of Protected Areas

64. Protected areas add some uncertainty because they often contain large stocks of biomass, but the extent to which the biomass is accessible for use as woodfuel is unclear. Some protected areas are completely inaccessible, others may be used for low-level extractive activities like collecting wood for household use, and still others might be legally inaccessible, but easily exploited due to poor enforcement. In this assessment, it was considered that all protected areas are equally difficult (but not impossible) to access for both self-collection and commercial extraction. This was accomplished by increasing the “friction” or effort required to travel within the boundaries of protected areas relative to unprotected areas with similar terrain. For this assessment, friction was increased by 90%, which

means that the likelihood of wood harvesting within protected areas was only 10% that of unprotected areas with similar terrain.

2.15.3 National boundaries and trade

65. The sustainability of woodfuel consumption within national boundaries can be affected by transboundary trade. For example, if Country-A has a major source of demand like a large urban center close to its border with Country-B, then it is possible that Country-A imports charcoal from Country-B. If that occurs, then County-A's woodfuel supply-demand balance could be affected favorably because those imports would reduce pressure on A's own resources. By the same token, Country-B's balance would be affected negatively by the additional removals.

66. In theory, MoFuSS can accommodate transnational trade; however, this is difficult in practice because there is no reliable data quantifying the magnitude of the trade. FAO's forest statistics database [35] includes woodfuel imports and exports, but the accuracy of this data is unclear and there is no information about trading partners

67. In this analysis, we have run separate regional models with semi-permeable national borders, resulting in some international flow of woodfuels within each region, but no flows between regions.[16] Within regions, crossing borders adds "friction" or travel time for wood suppliers, making it more costly, but not impossible, for people to access wood in neighboring countries. Our final model includes a mix of individual countries and countries clustered together to accommodate trade where we suspect it forms a significant fraction of overall woodfuel consumption. We explain this in more detail in the section on global divisions below.

2.15.4 Prune factor

68. There are some technical parameters related to spatial modeling that could also affect the outcome. MoFuSS decides which pixels are harvested in each time step (one year in the global model), and how much wood will be harvested, based on probability maps that integrate accessibility and woodfuels demand. However, actual wood harvesting is not entirely based on well-defined probabilities. When simulating annual wood harvesting by millions of people across a landscape represented by millions of pixels, there are stochastic or random elements that also drive people's decisions. To include this, we make assumptions about stochasticity by introducing a so-called "prune factor". This factor allows the model to run from fully deterministic in which people select pixels to harvest completely based on probability maps, to fully stochastic, in which people harvest from pixels in a completely random manner regardless of each pixel's accessibility.

69. The "prune factor" ranges between 0 and 100% and determines the extent of the landscape that will be visited by wood harvesters. Because this regional assessment is conducted at 1 km resolution, we choose 100% because it is realistic to think that every square kilometer may be visited at least once annually. However, for sub-national or project-level simulations, which could be modeled at 1 hectare or 30 m resolution, it is unrealistic for every pixel to be visited every year and we would adjust the prune rate to something less than 100%.

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[16] If accurate information on trade becomes available, we could tune our approach to align with the available data. However, collecting our own data is beyond the scope of this assignment.

2.15.5 Assigning fNRB to urban locations

70. MoFuSS was designed to assess the impacts of woodfuel consumption at the site of harvest. The model determines fNRB by considering the ratio of woodfuel harvesting to consumption within a specified area. This works at a national level because harvest and consumption are fully contained within national boundaries (assuming imports and exports are minimal). Wood harvest within urban areas is minimal, and most woodfuel-using urban households buy wood or charcoal that is brought from rural areas. Moreover, commercially harvested urban woodfuels tend to drive degradation more than woodfuels harvested for subsistence use by rural households because commercial extraction is more intense and spatially focused [36]. We estimate urban fNRB by assuming urban woodfuels originate from high-fNRB administrative units in rural areas and define urban fNRB in each country as the average of the upper 50% percentile of all rural administrative units.

71. The resulting calculations yield urban fRNB values that exceed national averages by two to seven percentage points (interquartile range) and are lower than the most impacted states, counties, or provinces by two to nine percentage points (also an interquartile range). Urban fRNB estimates are included in the full table of national results below.

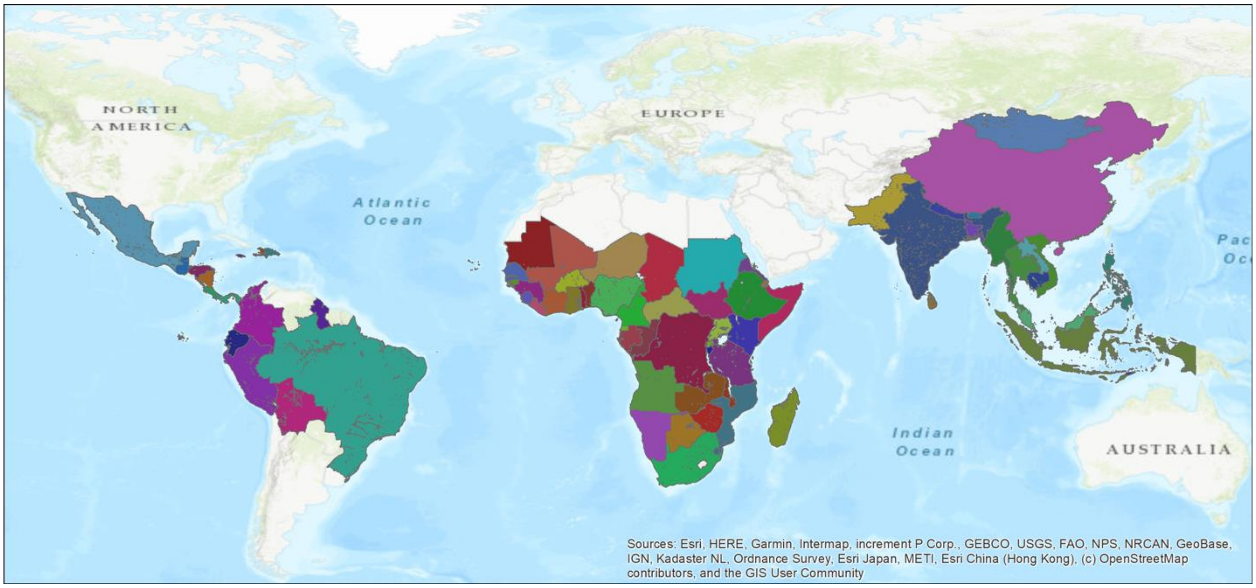
2.16 Global divisions

72. Originally, MoFuSS was developed for landscape-level analysis of individual interventions or clusters of projects. This assessment requires a global model, which presents significant challenges. Adapting MoFuSS for the global model involved integrating multiple countries with international borders that allow some trade of woodfuels. Initially, we built versions of MoFuSS that modeled large regional blocs, including several attempts to run models covering entire continents. However, it became apparent that MoFuSS cannot realistically simulate trans-border trade across numerous countries simultaneously without substantial recoding. With semi-porous borders between countries, MoFuSS simulated trade volumes and directions that, even in the absence of empirical data, seemed unrealistic. This is because, in MofuSS, woodfuel flows are determined primarily by pressure maps based on physical accessibility. However, transborder woodfuel trade is often illicit, and its flow and volume are influenced by many factors that are inherently difficult to model, particularly in the absence of any data to use as calibration.

73. As a result, to deliver this global assessment, we abandoned the attempt to model entire continents or large clusters of countries. Instead, we opted to model small clusters of countries where we have good evidence of transborder trade (for example, charcoal trade between Central African Republic, Cameroon, and Nigeria [37]). In contrast, countries where we lack evidence of trade or where MoFuSS produced unrealistic trade flows are isolated and woodfuels do not flow across their borders.

74. This combined approach resulted in 50 regions (**Figure 9**) to optimize processing time. This regional approach is particularly beneficial in cases where there is substantial evidence of significant charcoal trade between countries for the cooking sector.

Figure 9: Map showing 50 analyzed countries and country-clusters for the global MoFuSS assessment



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

3. Results

75. We would like to introduce the results section with some valuable and concise clarifications about how MoFuSS works and generates results.

76. First, MoFuSS produces a variety of results in various formats. The essential GIS-based results are available in the long run in this Google Drive folder[17]. To make spatial results easily queryable without the need for a Geographic Information System (GIS) software, we developed a prototype web-platform where both vector and raster results can be accessed and consulted, please visit www.mofuss.unam.mx, under *Default Scenarios*.

77. Second, to demonstrate how the uncertainty in input parameters leads to variation in fNRB and other outputs, MoFuSS can run multiple realizations. This technique, called Monte Carlo simulations, chooses randomly from a distribution of input parameters. For more info about uncertainty in MoFuSS, please see the section about sensitivity.

3.1 Updated fNRB values for low- and middle-income countries

78. We ran MoFuSS for 50 countries and clusters of countries, resulting in a total of 75 national estimates of fNRB. The raster-based analysis can be disaggregated to over 1,500 level-1 administrative units and over 20,000 level-2 administrative units.

79. **Table 5** shows a summary of national woodfuel harvesting, NRB, and fNRB (calculated as described in Equations 3-5 above). The table also includes standard deviations to provide an indication of uncertainty in national estimates of each variable. Standard deviations are derived from variance of NRB and fNRB resulting from each Monte Carlo simulation described in other sections of this report.

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[17] https://drive.google.com/drive/folders/1H6OqxALkgcuTzlLcCL32sqmEoB5LJGe5

80. Note, some of the results with low fRNB have large standard deviations and others are listed as "NA". The large standard deviations occur because it is a standard deviation of a ratio which is bounded between zero and one. This makes the standard deviation sensitive to small changes in the denominator of the ratio. In addition, the uncertainty of one key input parameter, r_{max}, is truncated to avoid physically impossible results, which leads to upward biases in the MC distributions that are especially apparent when the fRNB is small.

81. The table also includes standard deviations for wood harvesting. Woodfuel demand is a fixed input so that harvesting should not vary across Monte Carlo runs, leading to no variance. However, in some Monte Carlo runs, variations in growth rate can result in small amounts of unmet demand or variation in imports and exports, which lead to variation in national harvesting and small, non-zero standard deviations. **Figure 10** - 12 show regional maps of fNRB for 2020-2030 at the national level and increasingly granular sub-national levels. For tabulated results at the first and second administrative level please see the tables within the Google Drive folder[18] shared above.

82. **Figure 10** - 12 illustrate spatial averages of fNRB by national and sub-national administrative boundaries. As we explained above, these results are mathematically derived from spatial raster maps of woody biomass harvesting that leads to loss of tree cover, which are shown in Figure 13 and 14 below.

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[18] https://drive.google.com/drive/folders/1H6OqxALkgcuTzILcCL32sqmEoB5LJGe5

Table 5: National woodfuel harvests, NRB, and fNRB estimates for the period 2020 to 2030 and standard deviations

Region	ISO3	Country	NRB 2020-2030 (oven-dry tons)	St Dev NRB 2020-2030 (oven-dry tons)	Harvest 2020-2030 (oven-dry tons)	St Dev Harvest 2020-2030 [19] (oven-dry tons)	fNRB 2020-2030 (%)	St Dev fNRB 2020-2030 (%)	Urban fNRB (%)	St Dev urban fNRB (%)
ASIA	BGD	Bangladesh	97653620	17804924	249881477	60475851	39	30	61	30
ASIA	BTN	Bhutan	150125	39224	543231	0	28	26	34	37
ASIA	CHN	China	58634793	16579102	750258693	101248	8	28	10	48
ASIA	IND	India	83634440	21211343	1395575308	22994903	6	25	18	43
ASIA	IDN	Indonesia	2990619	3181724	64457333	11593	5	100	6	100
ASIA	MYS	Malaysia	329623	108843	972116	0	34	33	36	35
ASIA	MNG	Mongolia	398261	98429	3628687	0	11	25	15	30
ASIA	MMR	Myanmar	42806656	7220538	140559304	1647534	30	17	35	24
ASIA	NPL	Nepal	35798987	3173845	86615089	615417	41	9	44	9
ASIA	PAK	Pakistan	34693193	4433416	440506847	6215049	8	13	30	17
ASIA	PHL	Philippines	195244299	17693089	348830163	1313381	56	9	62	15
ASIA	KHM	Cambodia	8740064	2214571	45146093	3248465	19	26	27	33
ASIA	LAO	Laos	23670933	2210828	52111942	1845550	45	10	52	19
ASIA	THA	Thailand	21679959	9362737	117824700	1493120	18	43	26	37
ASIA	VNM	Vietnam	39986035	5017616	116113509	1926458	34	13	42	19
ASIA	LKA	Sri Lanka	24466771	4630868	58593803	35597	42	19	45	25
ASIA	TLS	Timor-Leste	1896947	428792	4790650	467	40	23	43	27
LATAM	BOL	Bolivia	1506439	655179	12821635	1298	12	43	16	49
LATAM	BRA	Brazil	16482391	4655580	127511095	0	13	28	19	48
LATAM	CRI	Costa Rica	231671	130620	2173147	15561	11	56	14	58
LATAM	GTM	Guatemala	39285599	3684718	93084686	743860	42	9	49	11
LATAM	HND	Honduras	13729276	1782611	43143135	320696	32	13	34	19
LATAM	NIC	Nicaragua	9811247	1567678	38638857	359801	25	16	30	21

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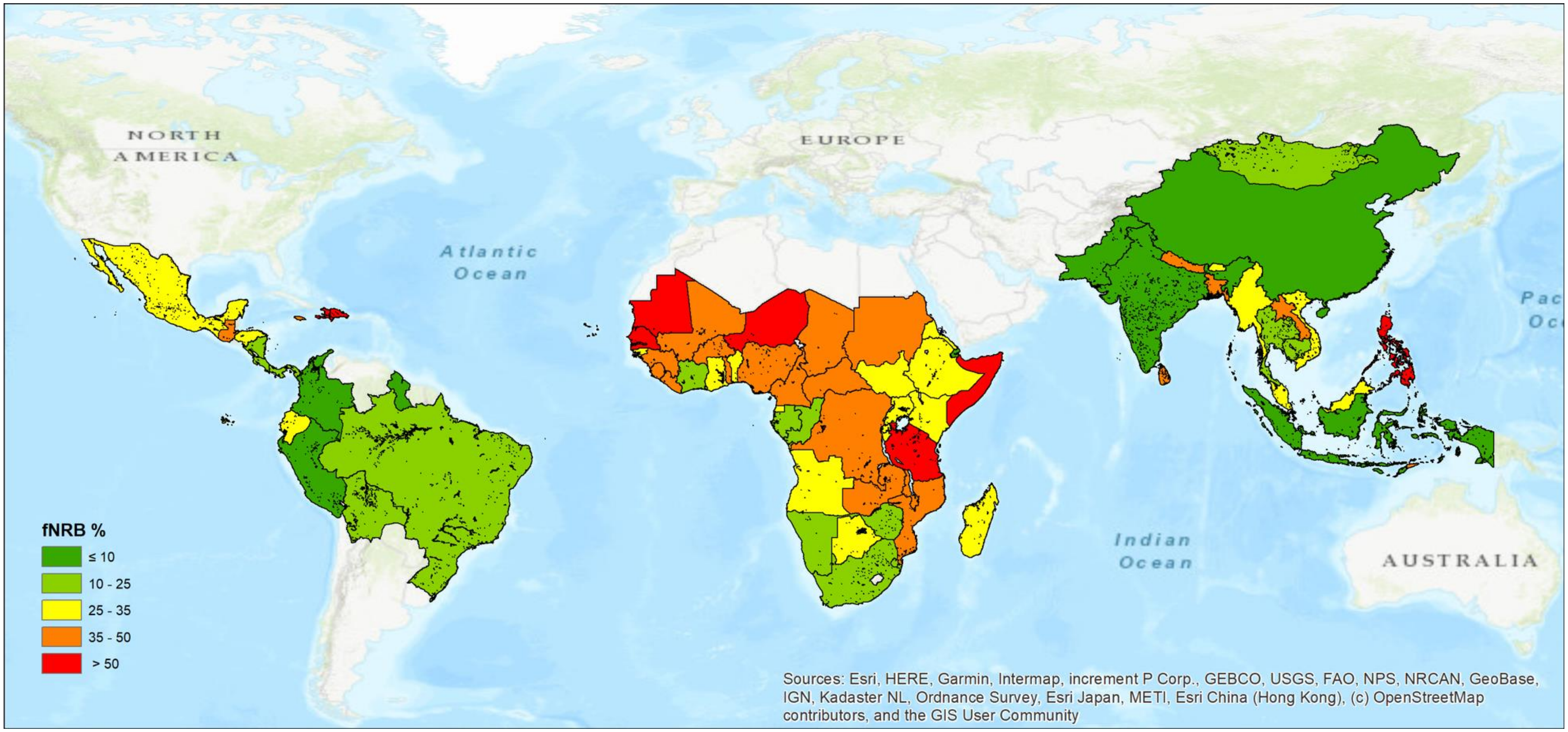
[19] Annual wood demand does not vary at the national level. However, harvesting varies between MC simulations in some countries as a result of variation in trade between model runs. In addition, in some MC runs, woodfuel demand may not be fully met, leading to small changes in harvesting from one run to the next and non-zero standard deviation across 30 MC runs.

Region	ISO3	Country	NRB 2020-2030 (oven-dry tons)	St Dev NRB 2020-2030 (oven-dry tons)	Harvest 2020-2030 (oven-dry tons)	St Dev Harvest 2020-2030 [19] (oven-dry tons)	fNRB 2020-2030 (%)	St Dev fNRB 2020-2030 (%)	Urban fNRB (%)	St Dev urban fNRB (%)
LATAM	PAN	Panama	763135	171426	3598781	44916	21	22	29	22
LATAM	COL	Colombia	1439157	917893	21224269	2	7	64	8	80
LATAM	DOM	Dominican Republic	66572664	4087249	107081696	2743216	62	7	64	9
LATAM	HTI	Haiti	33440650	1228503	47746513	2859165	70	7	75	11
LATAM	GUY	Guyana	4	22	26551	0	0	100		100
LATAM	JAM	Jamaica	3419055	540371	9367572	102	36	16	42	19
LATAM	MEX	México	62558160	5623342	220629062	46530	28	9	33	15
LATAM	ECU	Ecuador	2801391	529074	10721404	99935	26	19	36	24
SSA	BEN	Benin	34279020	5462658	105112761	96062	33	16	35	21
SSA	BFA	Burkina Faso	40514810	12704045	109623904	85615	37	31	49	37
SSA	BDI	Burundi	24350998	5843751	79674926	4580571	31	25	34	30
SSA	RWA	Rwanda	24504161	6080846	84402802	6499394	29	26	31	34
SSA	TCD	Chad	30941430	4682655	84846433	10071	36	15	47	21
SSA	CIV	Côte d'Ivoire	18267520	9211627	118044076	594	15	50	17	63
SSA	DJI	Djibouti	4954	1090	536263	9924	1	22	2	23
SSA	ERI	Eritrea	4659622	1193762	16644210	285641	28	26	32	39
SSA	ETH	Ethiopia	203522578	36293558	639993909	3770013	32	18	52	21
SSA	SOM	Somalia	165681007	24355041	276776173	2951897	60	15	62	18
SSA	GHA	Ghana	87611103	17021302	267322503	156133	33	19	35	25
SSA	KEN	Kenya	77159744	14934888	261373075	120021	30	19	38	32
SSA	MDG	Madagascar	85007898	14116954	250827121	10357	34	17	45	20
SSA	MOZ	Mozambique	139778627	15052824	368473606	4371910	38	11	41	14
SSA	MWI	Malawi	55150689	2860564	113221023	4244411	49	6	56	13
SSA	MLI	Mali	80102442	18166085	186573169	10201	43	23	49	26
SSA	MRT	Mauritania	16819290	3627369	26824316	14	63	22	65	27
SSA	NER	Niger	80469557	2150787	134007473	2539510	60	3	67	14
SSA	SDN	Sudan	64914838	11952289	133638215	2949876	49	19	57	20
SSA	SSD	South Sudan	40066348	7233017	120753013	2953175	33	18	36	18

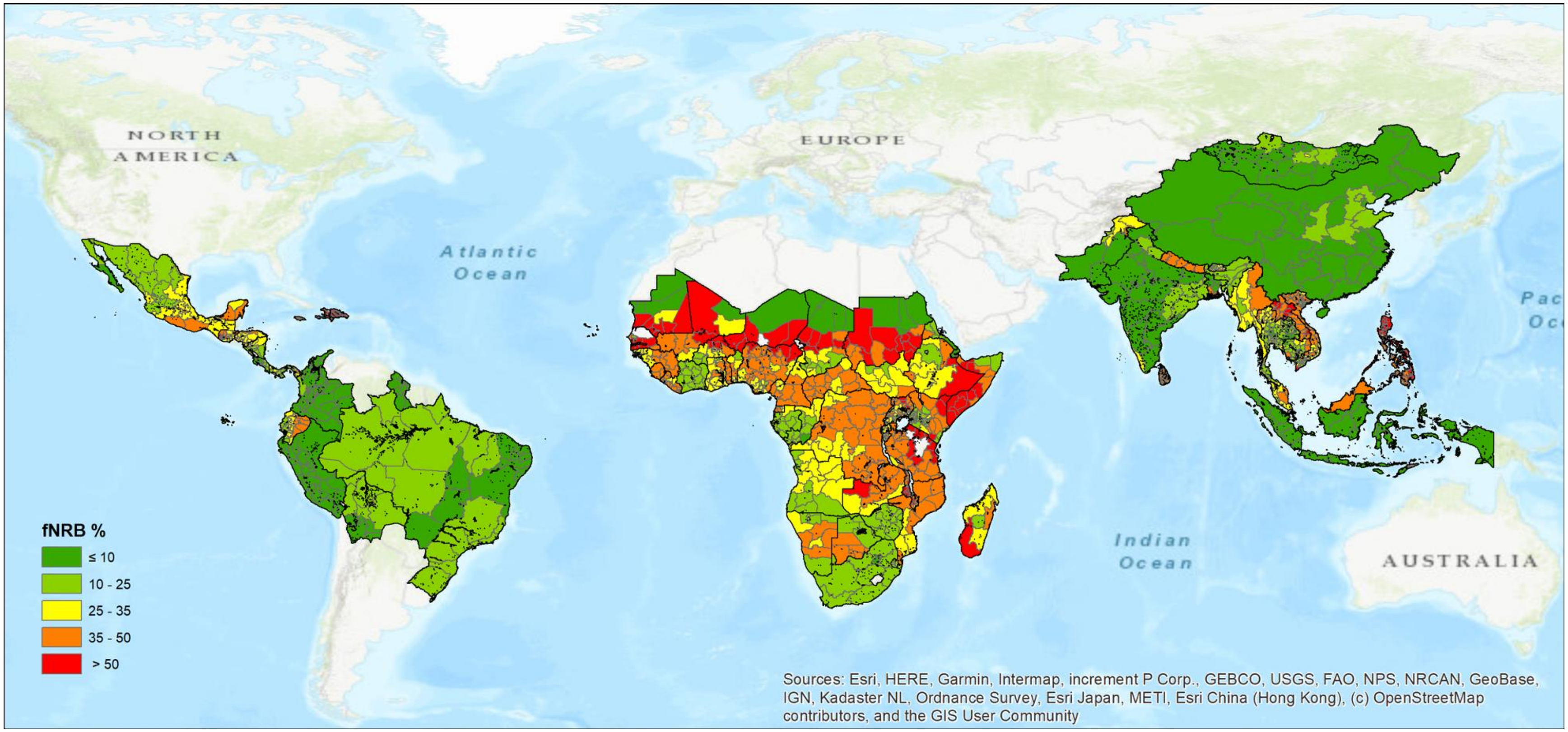
Region	ISO3	Country	NRB 2020-2030 (oven-dry tons)	St Dev NRB 2020-2030 (oven-dry tons)	Harvest 2020-2030 (oven-dry tons)	St Dev Harvest 2020-2030 [19] (oven-dry tons)	fNRB 2020-2030 (%)	St Dev fNRB 2020-2030 (%)	Urban fNRB (%)	St Dev urban fNRB (%)
SSA	GMB	Gambia	11738422	1737534	20455561	795070	57	15	64	12
SSA	SEN	Senegal	103255441	11832351	163583594	1010111	63	11	75	17
SSA	BWA	Botswana	1105261	330674	3317946	23	33	30	36	35
SSA	NAM	Namibia	991873	223436	3966001	108	25	23	40	24
SSA	SWZ	Swaziland	323221	134165	2289039	15	14	42	15	40
SSA	ZAF	South Africa	4818293	1707506	31086472	106	15	35	18	42
SSA	TZA	Tanzania	296507400	20365040	583934445	223358	51	7	59	13
SSA	TGO	Togo	35723926	6146276	76484635	198845	47	17	50	20
SSA	UGA	Uganda	152197355	28848612	437365457	1109017	35	19	41	24
SSA	CAF	Central African Republic	13518885	1824305	33634325	628443	40	14	44	17
SSA	CMR	Cameroon	55327096	12280626	143425627	1620956	39	22	45	30
SSA	NGA	Nigeria	350086901	41581567	898074955	2878149	39	12	44	18
SSA	GIN	Guinea	67442669	12887886	186219390	63755	36	19	39	22
SSA	GNB	Guinea-Bissau	3946542	889024	12168474	7817	32	23	34	25
SSA	LBR	Liberia	18423090	5935545	48901361	20654	38	32	40	34
SSA	SLE	Sierra Leone	33525658	5049893	83736427	77614	40	15	42	15
SSA	COG	Republic of the Congo	4923191	2651483	27306555	1336	18	54	25	63
SSA	GAB	Gabon	356133	263720	1654636	901	22	74	25	75
SSA	GNQ	Equatorial Guinea	441567	195214	1261261	419	35	44	37	47
SSA	ZMB	Zambia	92978499	11448781	243622526	19062	38	12	43	12
SSA	ZWE	Zimbabwe	12207335	5317595	62891875	1217	19	44	20	45

Figure 10: National fNRB values averaged over 2020-2030



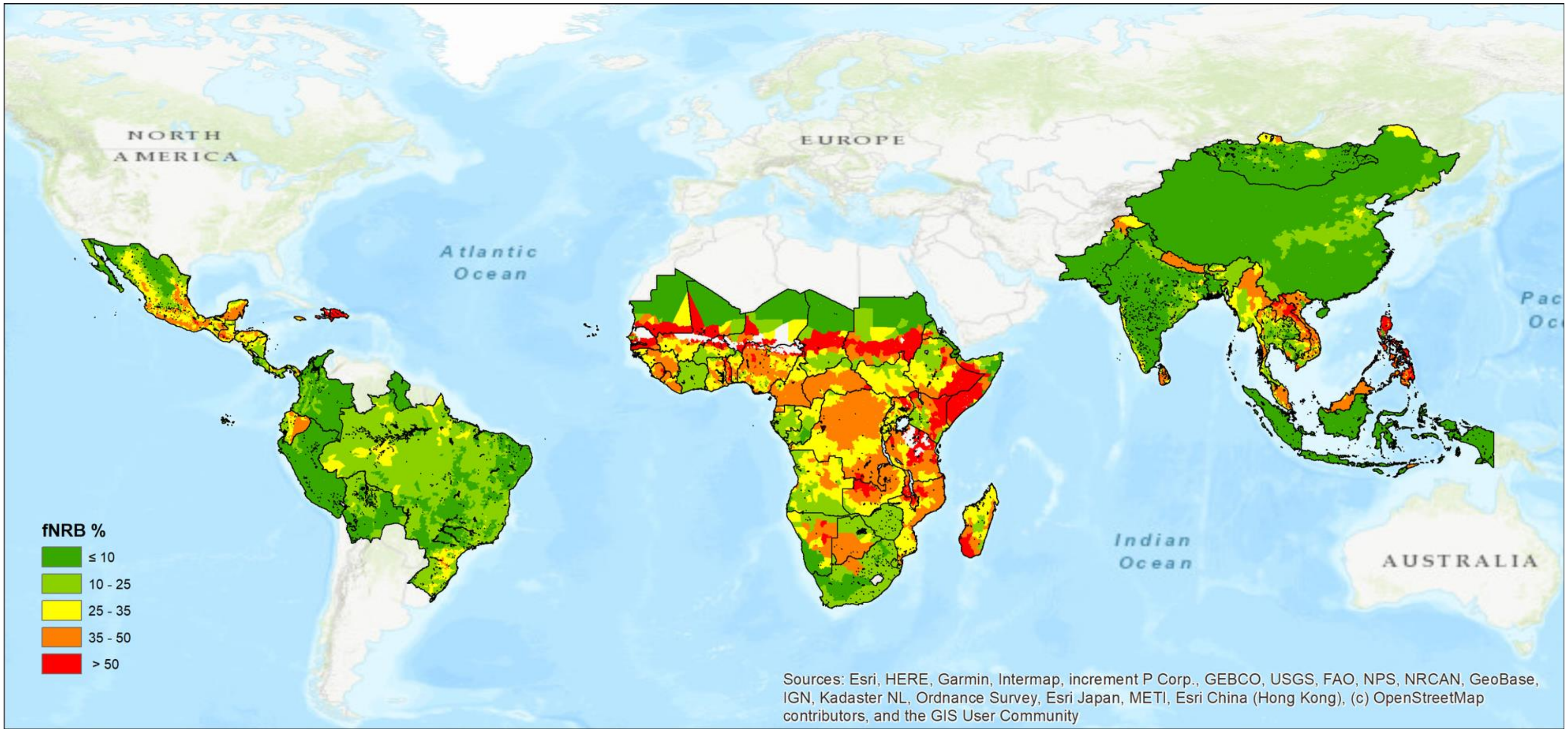
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 11: fNRB at the 1st administrative level averaged over 2020-2030



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

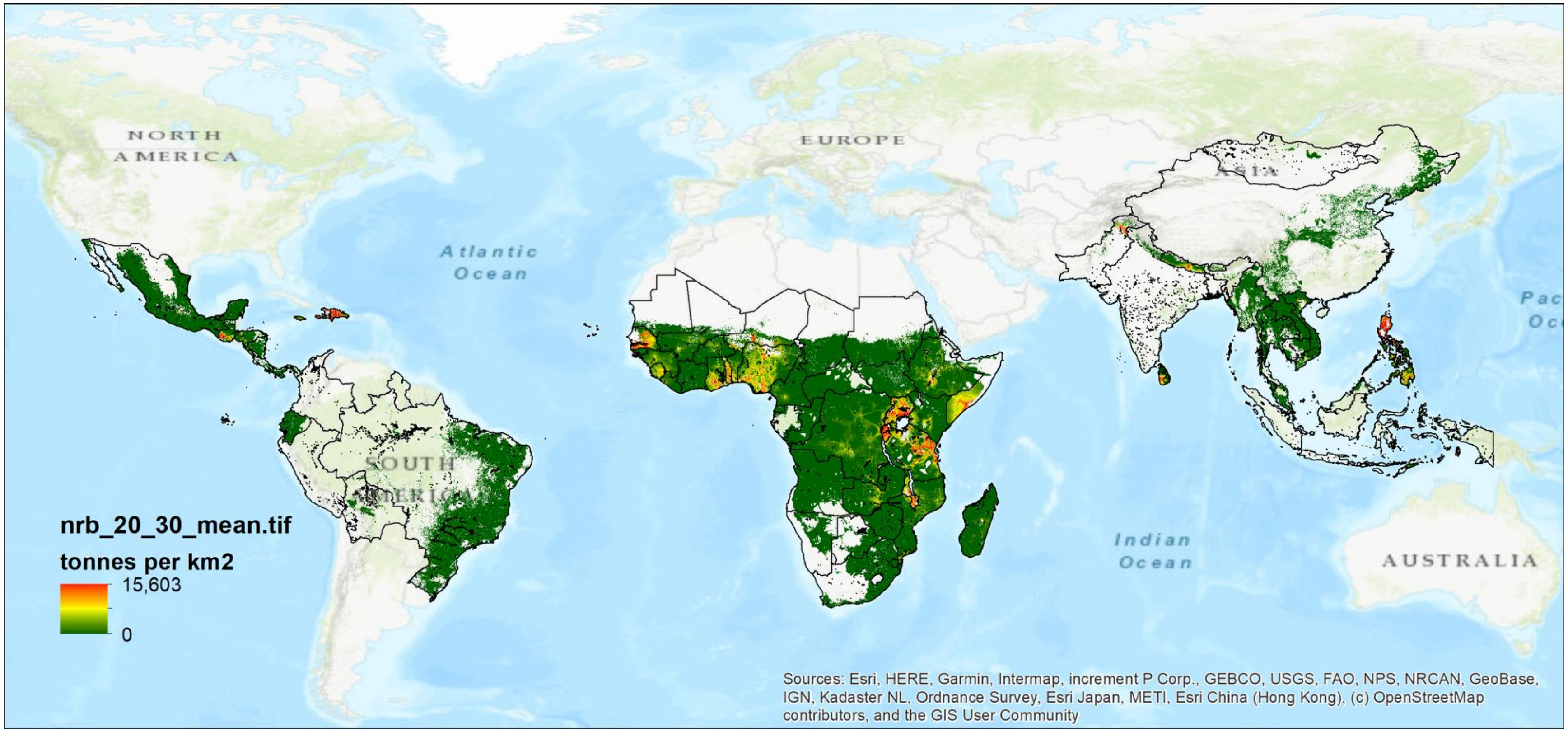
Figure 12: fNRB at the 2nd administrative level averaged over 2020-2030



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

83. By examining the maps in **Figure 10** - 12 it is clear that there is spatial variation across all world regions. For example, Southern Africa has lower fNRB than the other sub-regions. There is also variation across countries within sub-regions, and within countries at sub-national levels. There are many factors that could drive this variation, including infrastructure and accessibility, population density, tree cover at the start of the simulation, and woodfuel demand trajectories predicted by WHO's database. We cannot explain all of the sources of spatial variation in this report. However, some differences are likely driven by a few key variables. For example, the lower fNRB outcomes in Southern African countries are very likely due to lower demand relative to supply than in other sub-regions. We can take South Africa and Kenya to illustrate this point. Both countries have populations of over 50 million people, and both have substantial areas of arid or semi-arid land with little or no tree cover. The WHO estimates that in 2020, roughly 5 million people in South Africa used woodfuels as their primary cooking fuel [23]. In contrast, in Kenya, is only less half the size of S Africa, over 40 million people used woodfuels as their primary cooking fuel.

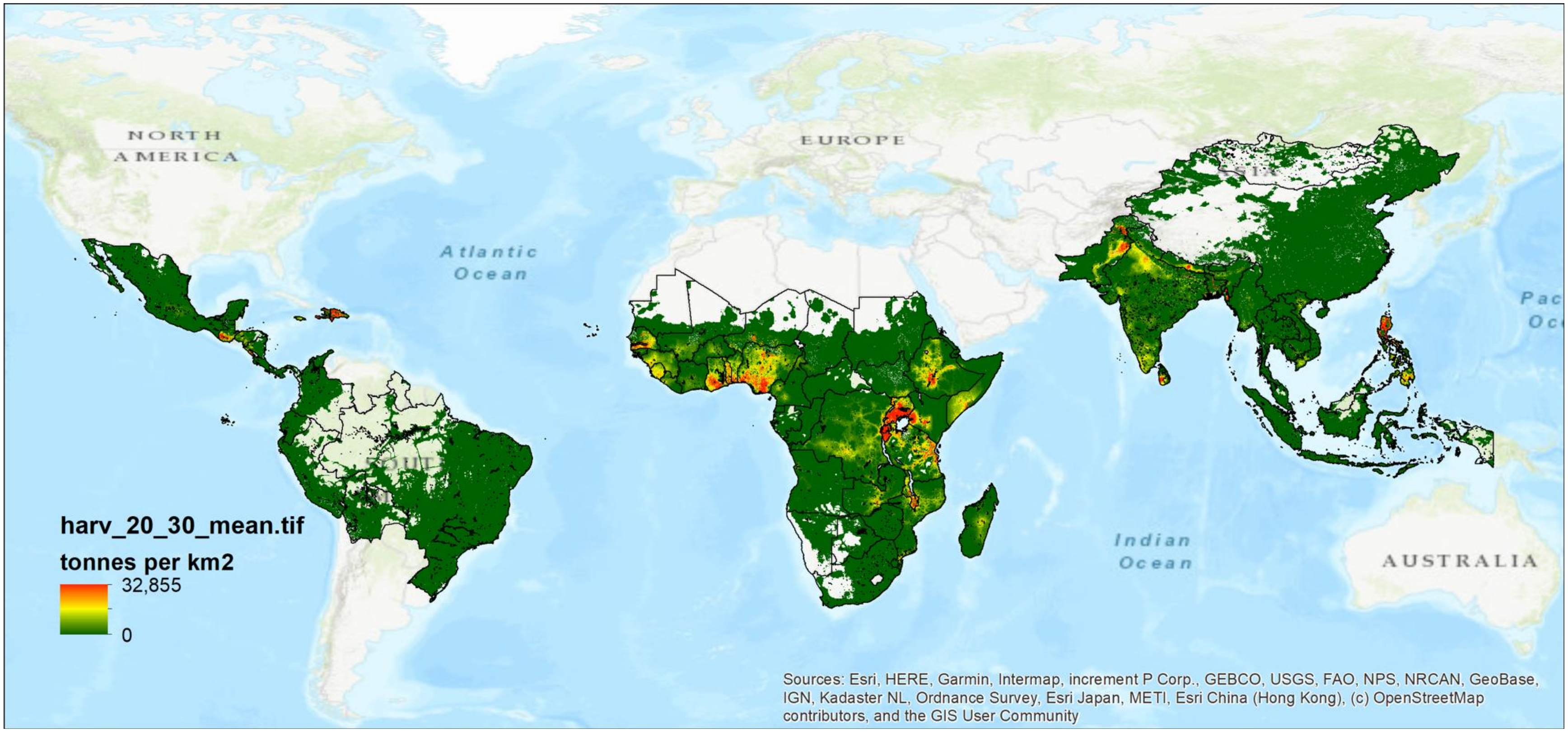
Figure 13: NRB values for the period 2020-2030 (ktons dry matter per km2)



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

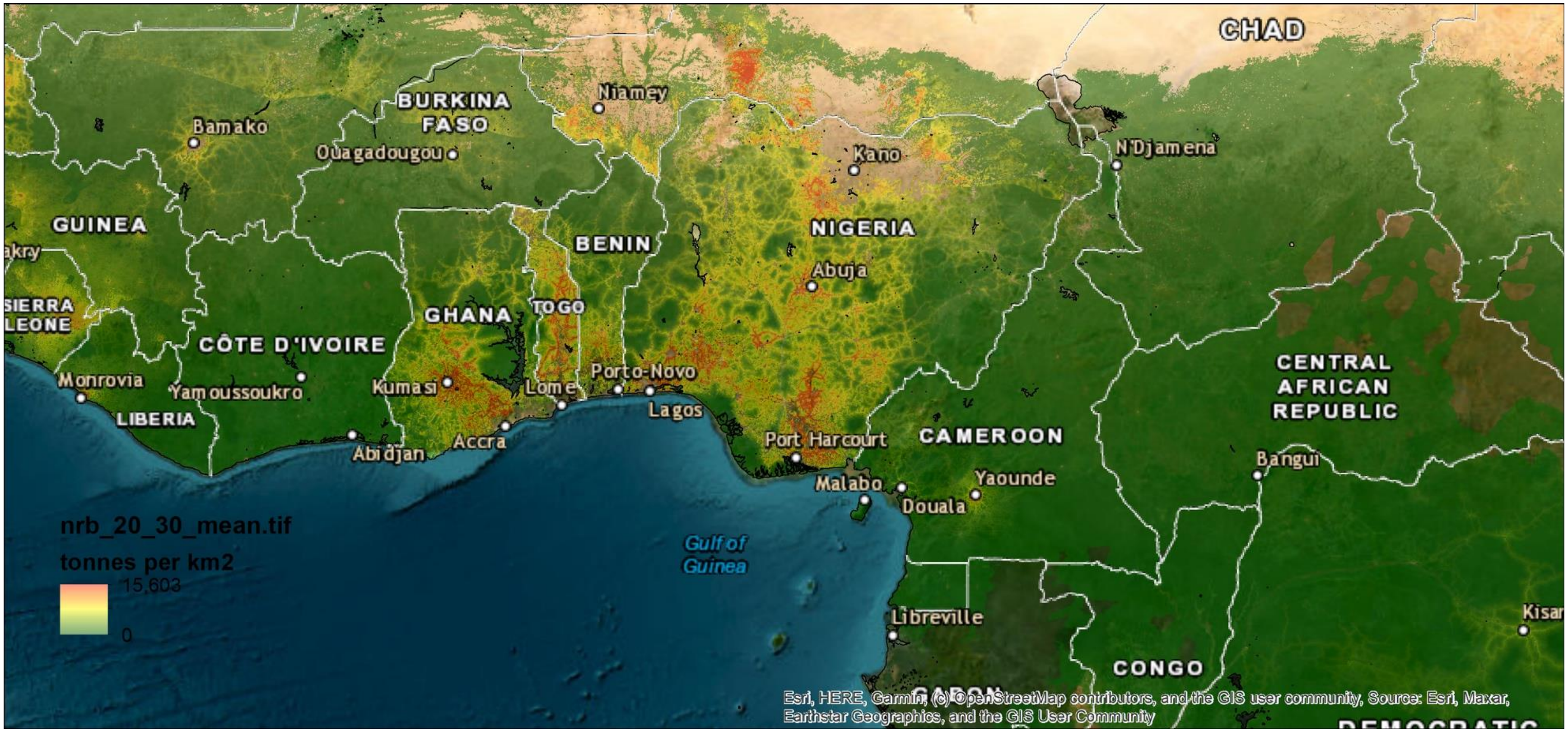
It is also instructive to zoom in for a more detailed view of the results. **Figure 15** - 17 show unsustainable harvest (NRB), overall harvest, and fNRB in the Gulf of Guinea region of West Africa.

Figure 14: Wood harvest for fuelwood and charcoal for the period 2020-2030 (ktons dry matter per km2)



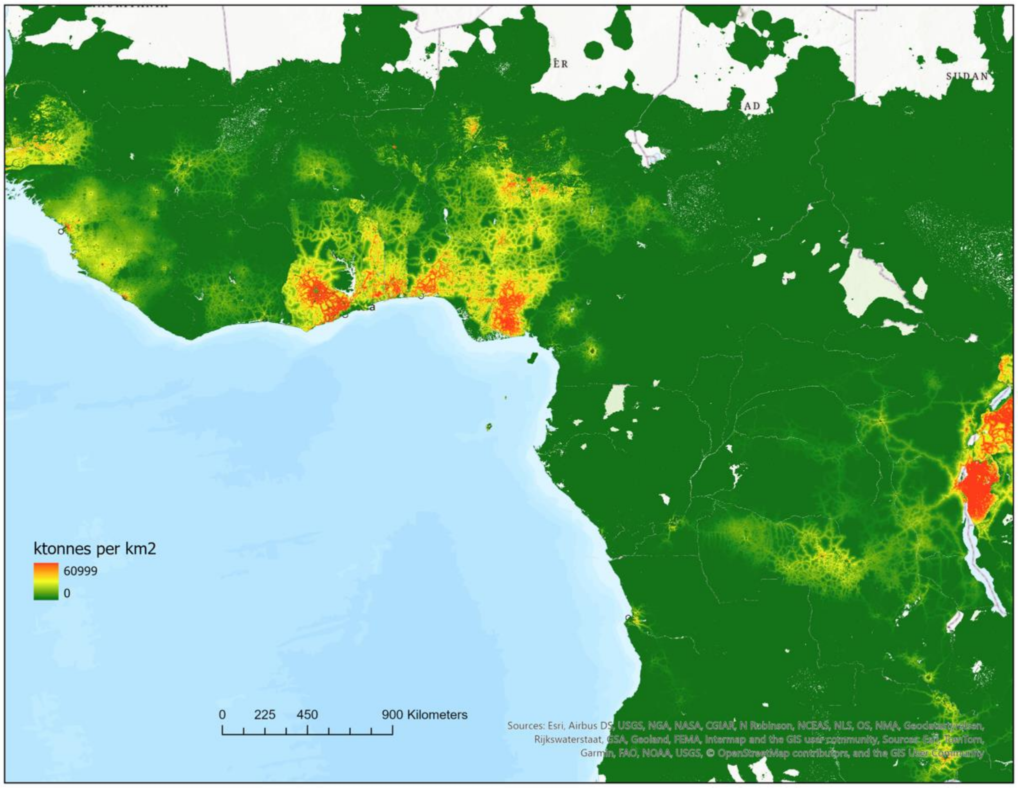
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 15: NRB values for the period 2020-2030 - zoom over Gulf of Guinea (ktons dry matter per km2)



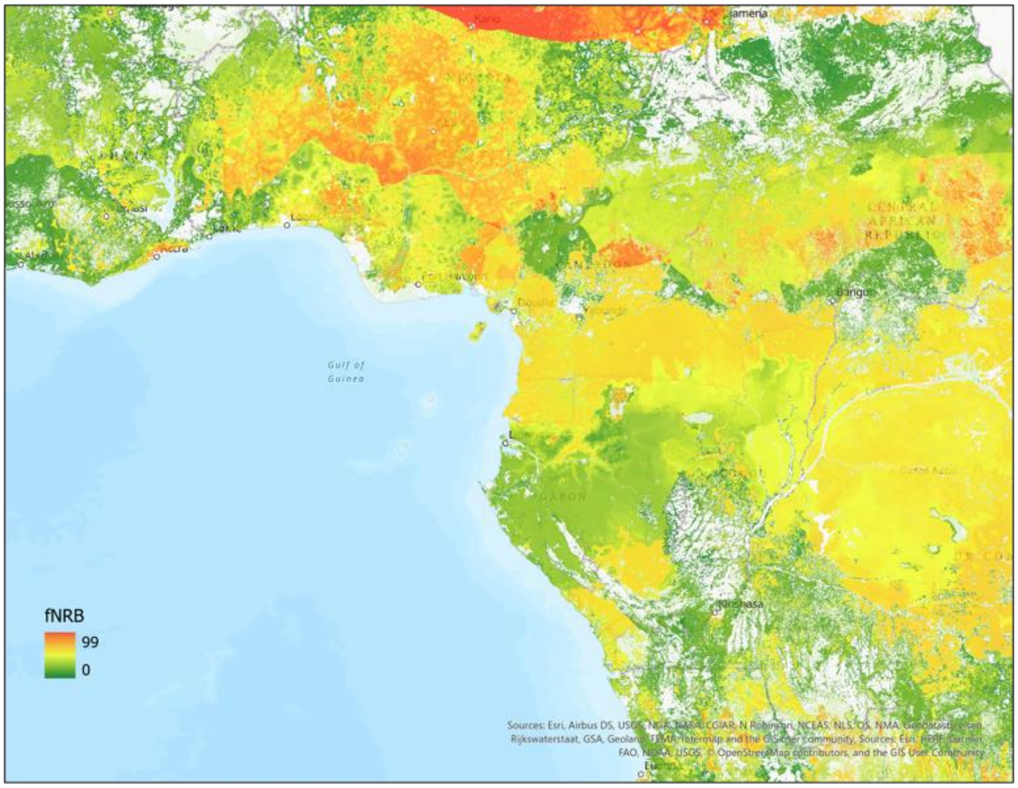
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 16: Harvest for fuelwood and charcoal 2020-2030 - zoom over Gulf of Guinea (ktons dry matter per km2)



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 17: fNRB values in each 1 km2 pixel for the period 2020-2030 - zoom over Gulf of Guinea



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

3.2 Uncertainty

84. Several of the input parameters are uncertain, which propagates through the analysis, affecting the key outcomes. We demonstrate this uncertainty by running Monte Carlo simulations. In this assessment, we focused on uncertainty in growth rates, which is the main driver of uncertainty in the model. We report uncertainties as standard deviations of harvest, NRB, and fNRB resulting from 30 Monte Carlo model runs in which each run includes a randomly selected value of "r_{max}", the parameter that defines the shape of the biomass growth functions for a given ecological zone, from a normal distribution of potential values.

85. Validating global simulation models with ground-based information is exceedingly difficult. If comprehensive, observed datasets with global coverage were readily available, there would be minimal need for simulations, except for projecting future scenarios. This presents a significant challenge as it limits the direct verification of the models against observed real-world data. As discussed in the following section, this is particularly true for woodfuel harvesting. While observed changes in Aboveground Biomass (AGB) are increasingly available at fine resolutions, attributing specific causes to these changes remains problematic.

86. Despite the complexities inherent in simulating woodfuel harvest and regrowth, the majority of the input maps and parameters used in the MoFuSS model are highly reliable. These inputs include well-validated layers such as population, biomass, land use cover, forest losses and gains, climate zones, and topography, among others. These layers are used in many studies that extend far beyond wood energy. Additionally, the displacement velocities of people walking and using vehicles have been measured by the MoFuSS team using GPS tracking in Honduras, India, and Malawi, supplemented by

Google Maps directions for longer highway distances. Moreover, AGB growth curves are derived from the best available data, specifically the IPCC 2019 revised reports, and are meticulously calibrated at the pixel level within the MoFuSS supply module. While a detailed list of all parameters, which currently exceeds 200, is too extensive to include in this summary, it is important to emphasize our strong confidence in the accuracy of the data incorporated into MoFuSS.

3.3 Proposed changes to TOOL30

87. Tool 30 provides guidelines for calculating fNRB without using explicit spatial analyses. The calculation requires project developers to have access to estimates of forest areas and forest productivity defined by the "mean annual increment" or MAI. For forest areas, the tool suggests using data from a 2000 FAO publication [38]. However, this is both outdated and inadequate because it ignores trees outside forests, which are important sources of woodfuel. If some version of TOOL30 is to be included in future methodologies, we suggest using more recent sources of land cover data that also account for trees outside forests. For example, the European Union's EU's flagship Copernicus programme provides free and open global land cover maps through 2019 which include 12 categories of forested land as well as shrubland, grassland, croplands, and other areas that are likely to include trees outside forests [39].

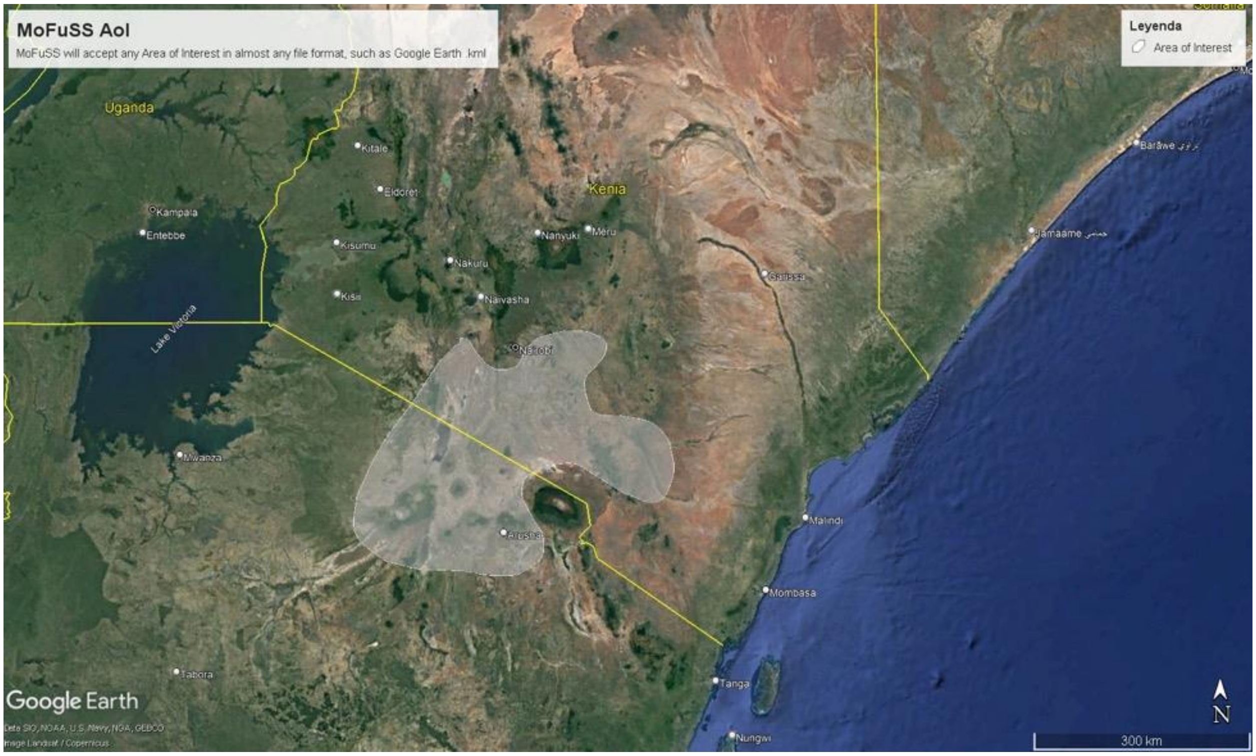
88. For biomass growth rates, TOOL30 recommends using Table 4.9 from the IPCC's 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories [18]. This is a more recent source of data, which makes it more appropriate for current estimates. However, the data presented for each land-use and land-cover category includes up to three values that vary with the age of the forest area in question. These growth rates can differ by up to a factor of 10. Project developers can obtain wildly different fNRB values depending on which growth rates are used. As with forest and non-forest areas, clearer guidance about the use of age-based MAI values is required if a version of TOOL30 is going to be used in future methodologies. For example, the Copernicus data cited above could be integrated with tree cover data from a source like Global Forest Watch [40] to create less ambiguous estimates of growth rates.

3.4 How sensitive are MoFuSS fNRB results to input parameters?

89. As we mentioned above, MoFuSS integrates sources of variations in input parameters. The model can also compare outputs of simulations using the key assumptions, but different input datasets (e.g. different land use cover maps). MoFuSS results are also sensitive to the spatial resolution, simulation period, and degree of stochasticity in the harvest "seeding" mechanism. In this section, we explore some of these sources of uncertainty using a small area lying on the border between Kenya and Tanzania (**Figure 18**), selected to enable quick processing of multiple Monte-Carlo runs.

90. We ran MoFuSS over the Area of Interest through five simulations, each using 30 Monte Carlo realizations. We used the same global datasets as for the full regional assessment, but varied the parameters listed in individually to demonstrate how each one affects over variability in outcomes. The five simulations included:
(a) No variation in input parameters
(b) Varying in maximum AGB stocks (K)
(c) Varying in growth rates (r_{max})
(d) Varying in the amount of prunable wood from Trees Outside Forests (TOF)
(e) Including stochasticity of harvest locations i.e. prune factor < 100%

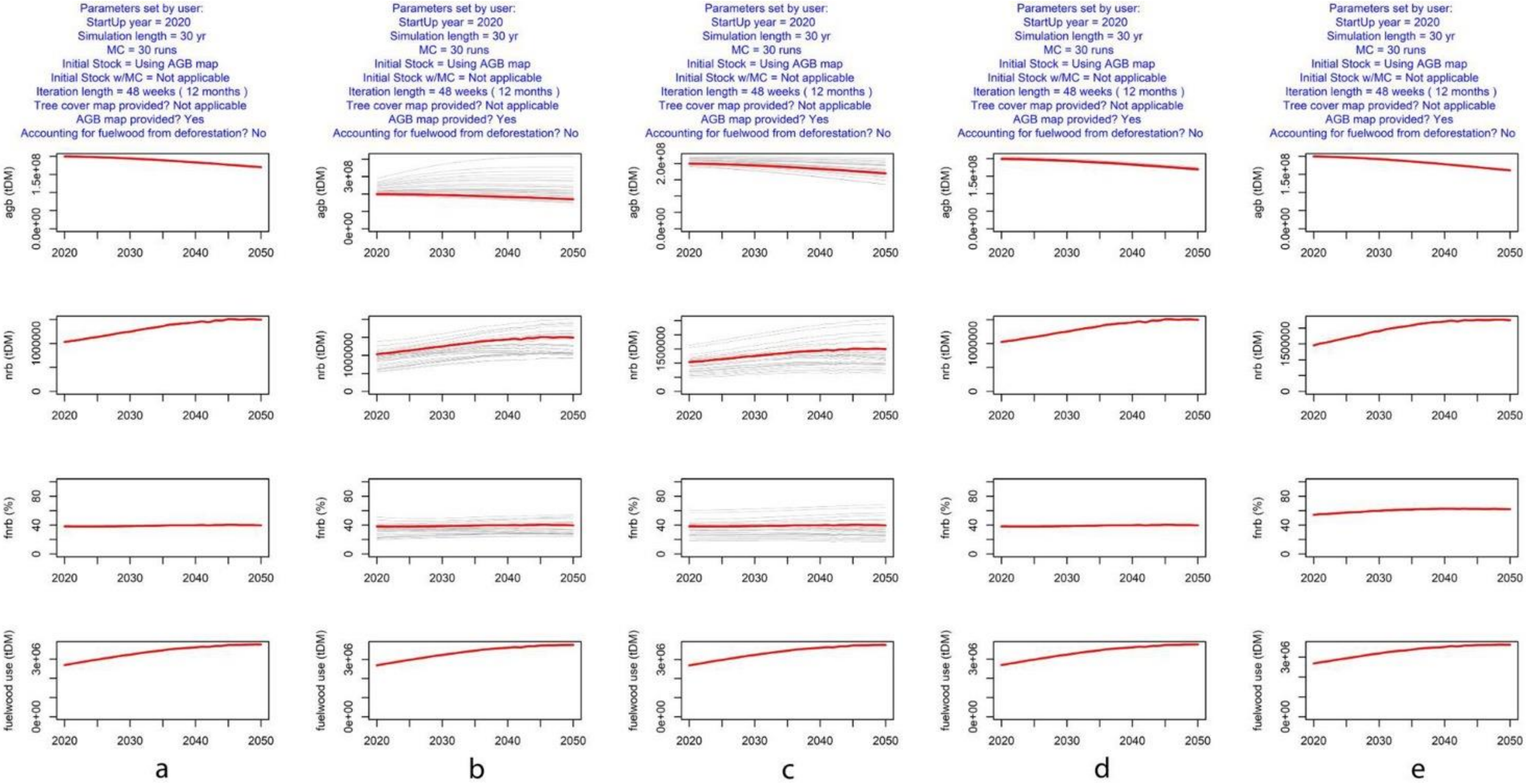
Figure 18: Case study to test for the sensitivity of woodfuel sustainability to input parameters variations



91. **Figure 19** shows temporal variations for the area of interest in the following key parameters (top to bottom): AGB, NRB, fNRB and total wood harvest for the five configurations described above (moving horizontally from a-e). It is apparent that results are most sensitive to parameters K (b) and r_{max} (c), which represent the maximum AGB stock and the maximum natural regrowth rate respectively (Please refer to in **Table 1** for details).

92. By comparing the magnitude of values and standard deviations in **Table 1**, it can be seen that both $r_{max\text{-}SD}$ and K_{SD} are uncertain. This is due to two factors: 1) natural variation across the landscape, or what we can call "real variation", and 2) errors in the AGB input layer. Regarding the first factor, we tried to minimize natural variation in K by compartmentalizing the landscape following broad regions, ecological zones, and land use cover; which resulted in 577 classes of K and r_{max} but some natural variability in unavoidable. Regarding the second factor, we are planning to improve MoFuSS to better accommodate the errors inherent in large spatial AGB maps; however, this is still a work in progress and was not prepared for this assessment.

Figure 19: Trajectories in aboveground biomass, NRB, fNRB, and woodfuel harvest for five MoFuSS settings, for 30 Monte Carlos runs (n=30)

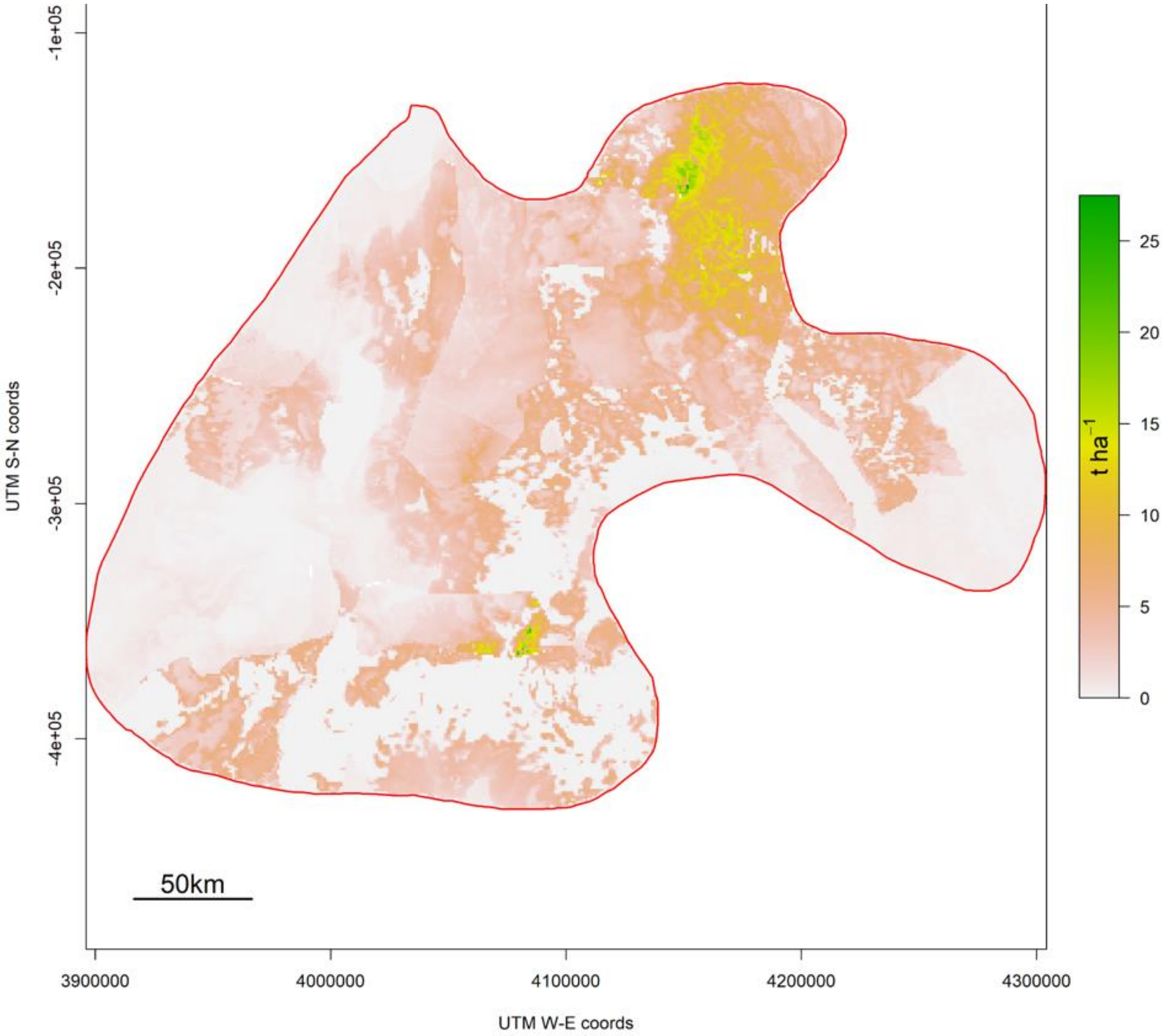


Note: a) No variation in input parameters is allowed; b) variation in maximum AGB stocks (K); c) variation if growth rate (rmax); d) variation in the prunable wood from Trees Outside Forests (TOF); e) stochasticity of harvest locations is turned on.

The red lines in represent the initial model run, which uses the main input parameters (r-max, K, etc). The gray lines represent the results of each Monte Carlo run, which are based on random selections from the distribution of possible values for each parameter. These plots show the distribution of responses after 30 MC runs.

93. Finally, **Figure 20** shows the spatial distribution of NRB's standard deviation when allowing all parameters to vary simultaneously. This last result goes beyond a sensitivity analysis but shows something of potential interest to project developers, donors, or other stakeholders, the possibility to depict where NRB and fNRB estimates are less certain and might deserve closer monitoring and verification.

Figure 20: Standard deviation of 2020-2030 NRB after 30 Monte Carlo runs allowing all parameters to vary simultaneously.



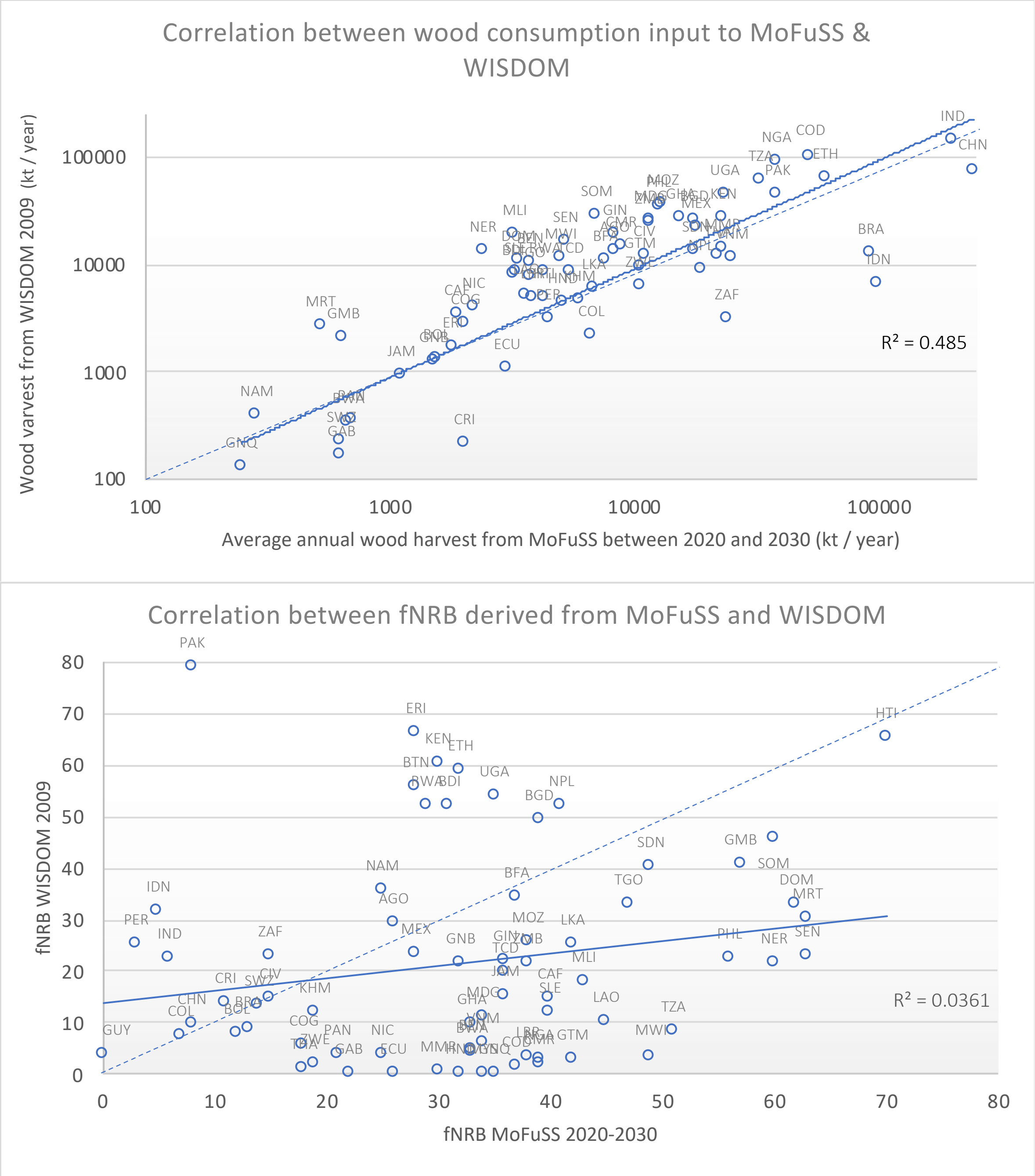
3.5 Comparison with the previous pan-tropical WISDOM study

94. As mentioned in the Introduction, a previous assessment published 2015, using data from 2009, [6] was the source of the 30% default value recommended by TOOL30. The difference between the previous study, using the WISDOM model, and the current study, using MoFuSS, were described in the Introduction. Here we compare biomass consumption and fNRB in the 75 countries that overlapped between the two studies. Despite using different assumptions and data sources to estimate woodfuel

demand, there is moderate correlation between annual woodfuel consumption (**Figure 21** - top). However, there is much lower correlation in fNRB derived from each study (**Figure 21** - bottom). This assessment found higher fNRB in roughly 2/3 of the 75 countries in common between the two studies (countries lying below the dashed line in the lower plot of **Figure 21**).

95. There are many factors that result in differences between the two assessments. In addition to differences in woodfuel consumption illustrated in the top of Figure 21, MoFuSS uses more recent and more accurate maps of population distribution, transportation infrastructure, AGB, and land cover classifications.

Figure 21: Scatter plot showing input woodfuel demand for MoFuSS and WISDOM (top – log scale) and national fNRB values (bottom). The dashed lines show the line along which results would be equal.



3.6 Changes between October 2023 and May 2024

96. After the preliminary release of fNRB results for Sub-Saharan Africa in October 2023, the CDM requested comments from all interested parties. Overall, 51 submissions were received with nearly 300 individual comments. In response to these comments, several critical inputs and modeling algorithms were revised. In addition, the analysis was expanded to encompass all countries with

significant populations that rely on traditional biomass. This expansion forced several additional modifications to the initial datasets and some model code. In this section, we briefly describe these revisions in order of the magnitude of impact they have on the MoFuSS output.

3.6.1 Population maps

97. The population dataset from Humanitarian Data Exchange (HDX) used in the previous analysis did not include several countries of interest to the clean cooking community. To include these countries and still use a single global dataset, the team transitioned from HDX to WorldPop. As a result, the number and spatial distribution of the population and urban/rural regions, may have changed. While these changes are not likely to have a large impact on results at the national level, they may lead to changes in the spatial distribution of demand, leading to different results for sub-national administrative units.

3.6.2 Revegetation Growth Curves

98. The MoFuSS submodule that generates revegetation growth curves was completely recoded based on comments from stakeholders with technical expertise in this topic. This revision automates previously disconnected code segments within MoFuSS, enhances transparency and reproducibility, and also changed growth rates in some regions, leading to higher or lower fNRB values.

3.6.3 Regional boundaries in Sub-Saharan Africa

99. Regional boundaries in Sub-Saharan Africa were revised and boundaries set for other regions. Originally the team planned to remove all "hard" boundaries and allow woodfuels to flow between neighboring countries. However, this led to very high trade volumes in some cases, which seemed unrealistic. To avoid these anomalous results, the team compromised by dividing SSA and other regions into a mix of individual countries and clusters of countries. Clusters were identified in part by recent analyses of transnational woodfuel trade in SSA [37,41]. This allows trade within a given cluster of countries but prevents trade between countries not included in that cluster. Hence, countries that were net importers (or exporters) in the assessment presented in October may no longer be net importers (or exporters) in the current study. This may result in higher (or lower) wood harvesting within a countries border, leading to different fNRB. In addition, the team increased the friction parameter at international borders within clusters of countries, which slightly reduced trade volumes.

3.6.4 Woodfuel consumption

100. Based on public feedback, fuelwood consumption was revised. The preliminary SSA assessment submitted in October 2023 used the CDM's default of 400 kg per person-year of air-dried wood. For SSA, this was adjusted to 400 kg oven-dry wood, which is equivalent to 500 kg air-dry wood. Wood consumption in other regions was chosen based on data from CDM and other sources (**Table 4**).

101. In addition, the team added estimates of non-residential wood consumption (explained above). These adjustments resulted in increased wood harvest, which leads to higher fNRB with other variables held constant.

3.7 Addressing large differences between Oct 2023 and the current release

102. When comparing results the results of the current release to the results from 43 countries in sub-Saharan Africa released in October 2023, we see that the majority of the updated national fNRB

estimates are within 10% of the previous assessment, and nearly two thirds are higher than previous estimates. The increases in fNRB are primarily due to the inclusion of non-residential demand, which led to higher wood consumption. However, several of the updated estimates are lower than the previous assessment, and a few results differ substantially from the October results. While there is insufficient space to explain every result that differs, in this section we consider several of the countries with large differences to understand the underlying reasons.

3.7.1 Small Island States: São Tomé and Príncipe and Comoros

103. Small islands are difficult to model within a broader global assessment at 1 km^2 resolution. SSA includes several small island states such as São Tomé and Príncipe and the Comoros Islands. In the October 2023 assessment, both countries were included in broader sub-regions: São Tomé and Príncipe with Central/West Africa, and Comoros with East Africa. When we created pressure maps for the broader regions, the small island countries were included which resulted in several inaccuracies that biased fNRB downward. As a result, simulated wood harvesting was just 5-7% of forecast demand in each country. With very little harvesting, there was minimal impact on tree cover and fNRB in each country was very low. For the reassessment, both island states were isolated from the SSA mainland, which removed the distortions. In addition, the updated population maps showed higher populations in both countries. As a result, in the revised assessment, woodfuel demand in both countries was higher than in the October 2023 assessment, and supplied entirely by domestic harvesting. These changes resulted in much higher fNRB. Indeed, the latest results show that both São Tomé and Príncipe and Comoros have the highest national fNRB of all the countries included in this assessment. However, we believe that the high values are caused by the coarse resolution used in this assessment. For this reason, we have omitted these small islands from the results. Projects seeking to earn carbon credits from projects in São Tomé and Príncipe and Comoros islands should implement a MoFuSS model at higher resolution.

3.7.2 Djibouti

104. Djibouti is also a small country, though not an island. There, results changed dramatically in the opposite direction. The October 2023 assessment found that Djibouti's fNRB was 61%. In the latest assessment, it is just 1%. Reasons for this are related to the way Djibouti is clustered with other countries. For the recent assessment, Djibouti was clustered with neighboring countries of Ethiopia Eritrea, and Somalia. These countries, though semi-arid, have significantly more tree cover than Djibouti. In addition, charcoal comprises the majority of Djibouti's woodfuel demand. Thus, MoFuSS projected that with trade enabled, the majority of woodfuel is imported from neighboring countries, leading to minimal domestic supply and very low fNRB.

3.7.3 Kenya

105. While most national fNRB estimates in SSA increased between October 2023 and the current assessment, our estimate of fNRB in Kenya decreased from 46% to 30%, with substantial sub-national variation. The main reason for this difference is that in the October assessment, Kenya was included in a region with other East African countries, including several countries with large and increasing demand for woodfuel like Tanzania and Uganda. In contrast, woodfuel demand in Kenya is projected to decline between now and 2030. However, the October assessment allowed trade of woodfuels between each country and the model projected that Kenya's wood harvest exceeded domestic demand by 70%, while Uganda and Tanzania harvested 8% and 28% below their demand respectively. Thus, in that simulation, Kenya was major exporter of woodfuels to Uganda and Tanzania. This seems

highly unlikely. In fact, while quantitative data not available, anecdotal evidence and one qualitative study [41] indicate that Kenya imports woodfuels from several of its East African neighbors.

106. Our reassessment avoids this outward flow of woodfuel from Kenya by isolating the three East African countries, preventing any trade. This may also be inaccurate; however, the team considered this the most appropriate approach given our lack of quantitative information about woodfuel trade in the region. As a result, even with the inclusion of non-residential woodfuel demand and increased per capita residential consumption, the overall woodfuel harvest between 2020 and 2030 in the current update is 22% lower than in the October analysis, resulting in lower fNRB.

4. Key background reading

1. The following papers are downloadable from in this Google Drive folder (no permissions needed):

1. R Bailis, R Drigo, A Ghilardi, O Masera, The carbon footprint of traditional woodfuel, *Nature Climate Change*, 2015, https://www.nature.com/articles/nclimate2491

   This paper describes the 2015 global WISDOM model

2. A Ghilardi, R Bailis, JF Mas, M Skutsch, et al. Spatiotemporal modeling of fuelwood environmental impacts: Towards improved accounting for non-renewable biomass, *Environmental Modelling & Software*, 2016 https://doi.org/10.1016/j.envsoft.2016.04.023

   This paper describes the original MoFuSS model in detail. Some steps have changed, but the underlying concepts are very similar to those described here.

3. A Ghilardi, A Tarter, R Bailis, Potential environmental benefits from woodfuel transitions in Haiti: Geospatial scenarios to 2027, *Environmental Research Letters*, 2018 https://iopscience.iop.org/article/10.1088/1748-9326/aaa846/meta (open access)

   This paper describes an early application of the MoFuSS model. It demonstrates how comparing BAU to alternate scenarios can result in an estimate of net biomass stock change and wrestling carbon emission reductions.

4. E Floess, A Grieshop, E Puzzolo, D Pope, N Leach, Scaling up gas and electric cooking in low-and middle-income countries: climate threat or mitigation strategy with co-benefits? *Environmental Research Letters*, 2023 https://scholar.google.com/scholar?oi=bibs&cluster=8368221658100548301&btnI=1&hl=en (open access)

   This paper doesn't apply MoFuSS or other spatial techniques; however, it uses WHO fuel choice projections to develop BAU scenarios that are used in a climate model.

5. References cited

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[2] CDM 2008 *AMS-I.E: Switch from non-renewable biomass for thermal applications by the user (Version 1.0)* (Bonn, Germany: CDM)

[3] CDM 2008 *AMS-II.G: Energy efficiency measures in thermal applications of non-renewable biomass (Version 1.0)* (Bonn, Germany: CDM)

[4] The Gold Standard Foundation 2008 *Indicative Programme, Baseline, and Monitoring Methodology for Improved Cook-Stoves and Kitchen Regimes* (Geneva: The Gold Standard Foundation)

[5] CDM 2022 Methodological TOOL30: Calculation of the fraction of non-renewable biomass (Version 04.0) *Approved SSC methodologies*

[6] Bailis R, Drigo R, Ghilardi A and Masera O 2015 The Carbon Footprint of Traditional Woodfuels *Nature Climate Change* **5** 266–72

[7] Drigo R Wisdom *Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM)*

[8] Bailis R, Wang Y, Drigo R, Ghilardi A and Masera O 2017 Getting the numbers right: revisiting woodfuel sustainability in the developing world *Environmental Research Letters* **12** 115002

[9] Ghilardi A, Bailis R, Mas J-F, Skutsch M, Elvir J A, Quevedo A, Masera O, Dwivedi P, Drigo R and Vega E 2016 Spatiotemporal modeling of fuelwood environmental impacts: Towards improved accounting for non-renewable biomass *Environmental Modelling & Software* **82** 241–54

[10] Ghilardi A, Tarter A and Bailis R 2018 Potential environmental benefits from woodfuel transitions in Haiti: Geospatial scenarios to 2027 *Environmental Research Letters* **13**

[11] Spawn S A and Gibbs H K 2020 Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010 *ORNL DAAC*

[12] Bouvet A, Mermoz S, Le Toan T, Villard L, Mathieu R, Naidoo L and Asner G P 2018 An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR *Remote Sensing of Environment* **206** 156–73

[13] Eggleston S, Buendia L, Miwa K, Ngara T and Tanabe K 2019 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories *Institute for Global Environmental Strategies, Hayama, Japan*

[14] FAO 2013 Global Ecological Zones (second edition) *FAO Map Catalog*

[15] Buchhorn M, Smets B, Bertels L, Roo B D, Lesiv M, Tsendbazar N-E, Herold M and Fritz S 2020 Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2017: Globe

[16] FAO 2019 GSOCmap1.5.0 *Global Soil Organic Carbon Map V1.5 (GSOCmap)*

[17] IPCC 2006 *2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 4 Agriculture, Forestry and Other Land Use* (Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies (IGES))

[18] IPCC 2006 *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies (IGES))

[19] MININFRA 2020 *National Survey on Cooking Fuel Energy and Technologies in Households, Commercial and Public Institutions in Rwanda* (Kigali, Rwanda: Ministry of Infrastructure and Ministry of Finance)

[20] MEMD 2021 *NATIONAL FIREWOOD AND AGRO RESIDUE SURVEY FOR UGANDA 2020* (Kampala, Uganda: Ministry of Energy and Mineral Development)

[21] Ministry of Energy 2002 *Study on Kenya's Energy Demand, Supply and Policy Strategy for Households, Small Scale Industries and Service Establishments: Final Report* (Nairobi: KAMFOR Company Limited)

[22] Ministry of Energy 2019 *Kenya Cooking Sector Study: Assessment of the Supply and Demand of Cooking Solutions at the Household Level* (Nairobi, Kenya: Kenya Ministry of Energy and Clean Cooking Association of Kenya)

[23] Stoner O, Lewis J, Martínez I L, Gumy S, Economou T and Adair-Rohani H 2021 Household cooking fuel estimates at global and country level for 1990 to 2030 - Supplemental Data *Nat Commun* **12** 5793

[24] World Health Organization 2021 Household air pollution data *Air pollution data portal*

[25] Harris N, Goldman E and Gibbes S 2019 Spatial Database of Planted Trees (SDPT) Version 1.0. *Global Forest Watch Open Data Portal*

[26] CDM 2022 *Methodological TOOL33: Default values for common parameters* (Bonn, Germany: CDM)

[27] FAO 2004 *Unified bioenergy terminology (UBET)* (Rome: FAO Forestry Department Wood Energy Programme)

[28] IPCC 1997 *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual* (Oxford, UK: Blackwell Press)

[29] Bailis R 2009 Modeling climate change mitigation from alternative methods of charcoal production in Kenya *Biomass and Bioenergy* **33** 1491–502

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[33] Hosonuma N, Herold M, Sy V D, Fries R S D, Brockhaus M, Louis Verchot, Arild Angelsen and Erika Romijn 2012 An assessment of deforestation and forest degradation drivers in developing countries *Environmental Research Letters* **7** 044009

[34] Munslow B, Katerere Y, Ferf A and O'Keefe P 2013 *The Fuelwood Trap: A study of the SADCC region* (Taylor & Francis)

[35] FAO Statistics Division 2023 FAOSTAT *Forestry Production and Trade*

[36] Masera O R, Rob Bailis, Rudi Drigo, Adrian Ghilardi and Ilse Ruiz-Mercado 2015 Environmental Burden of Traditional Bioenergy Use *Annual Review of Environment and Resources* **40** 121–50

[37] Sola P, Schure J, Gambo J, Awono A, Mwaanga B M, Moombe K B, Nlom J H, Hiol-Hiol F and Banda E 2021 *Cross-border charcoal trade in selected east, central and southern African countries: A call for regional dialogue* (CIFOR)

[38] FAO 2000 *Global Forest Resources Assessment 2000* (Rome: UN Food and Agriculture Organization)

[39] Buchhorn M, Smets B, Bertels L, Roo B D, Lesiv M, Tsendbazar N-E, Herold M and Fritz S 2020 Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe

[40] World Resources Institute 2023 Global Forest Watch - Interactive Map

[41] Haysom S, McLaggan M, Kaka J, Modi L and Opala K 2021 *Black Gold: The charcoal grey market in Kenya, Uganda, and South Sudan*

Appendix 1. Accessing Code, datasets, and results

MoFuSS main webpage

URL: https://www.mofuss.unam.mx

1. Description and usage: To make spatial results easily queryable without the need for a Geographic Information System (GIS) software, we developed a web-platform where both vector and raster results can be accessed and consulted. Please, visit the prototype visualization tool under *Default Scenarios.*

Results repository

URL: https://drive.google.com/drive/folders/1ZgC-upHUDNZt87fYlR77rpEc_IKT7Y2O?usp=drive_link

See also: https://is.gd/KLEZcC

Description and usage: This folder is linked to MoFuSS post processing codes and might be replenished or modified when running new MoFuSS scenarios over different areas or for different time periods. Final results aren't erased and will remain here for the time being. However, while MoFuSS updates the folder content, some files may take up to one or two minutes to "reappear". If you believe a certain file is missing, please wait for about 2 to 3 minutes and check back. Otherwise, please contact aghilardi@ciga.unam.mx and/or rob.bailis@sei.org

Code repositories

URL: https://gitlab.com/mofuss/mofuss

Description and usage: MoFuSS is an open-source freeware in constant development. There is no restriction to access the code. For the case that someone would like to collaborate within our GitLab project, please email aghilardi@ciga.unam.mx or ask to be invited directly from your GitLab account. We are working to improve the MoFuSS documentation, which can also be accessed in the same GitLab address.

Datasets repositories

URL:

https://code.earthengine.google.com/92c0e63070a94070cb62121141eba8b3

MoFuSS does not use backup datasets. Instead, it employs GEE (Google Earth Engine) scripts to download and preprocess all input datasets at any given resolution and for any area of interest.

Key references

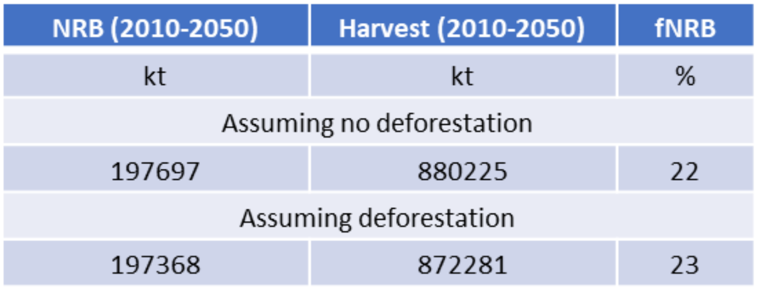
URL: https://is.gd/9R9OjX

Appendix 2. Why was the deforestation module not used?

1. As mentioned above, one of the main and innovative features of MoFuSS is the capacity to run an underlying prospective model of forest losses and gains, which is validated with independent data and allows to simulate future deforestation and gain events. For the cases of losses (i.e. deforestation), these events translate into a sudden availability of wood at the event location, followed by a longer term reduction of wood in the years to follow until natural regrowth takes over. With gains is just the opposite, non harvestable pixels will become harvestable after a gain event predicted by the prospective land change module.

2. However, for this global study we disabled this feature for several reasons. First, it was very difficult to calibrate a single model across large areas, leading to unacceptably low validation rates of just 10 or 20%. Second, landscape prospective models are intended to be used at a similar resolution as the input data (30 m in this case). Aggregating 30m data to 1km results in inaccurate deforestation patterns because the total amount of deforested area must be maintained regardless of resolution. At lower resolutions, this "concentrates" deforestation into fewer areas because of the size of each pixel. Third, the wood that becomes available from deforestation is only available for the year of the event and only within a limited area. Last, the impacts of heavy deforestation on NRB and fNRB in heavily deforested areas were minimal. For example, Table 6 shows results from a simulation using only Ghana.

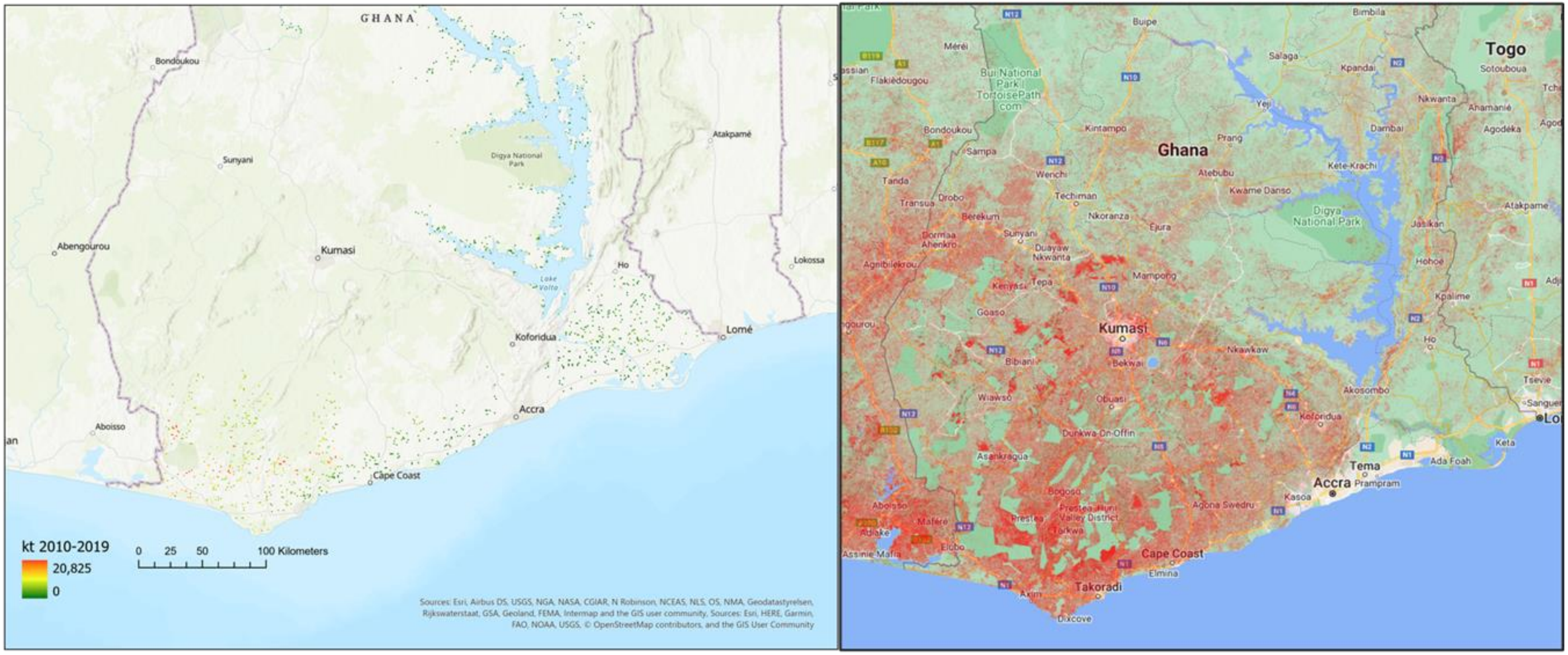
Table 6: Comparison in NRB, harvest and fNRB values for Ghana assuming deforestation versus no deforestation in the simulation period 2010-2050



NRB (2010-2050)	Harvest (2010-2050)	fNRB
kt	kt	%
Assuming no deforestation		
197697	880225	22
Assuming deforestation		
197368	872281	23

Note: Results are shown for no variation in parameters except for the deforestation submodule turned on and off. These results were not included into the sensitivity analysis as we believe they deserve a more detailed treatment.

Figure 22: Simulated deforestation patterns as predicted by MoFuSS for Ghana for years 2010 to 2019 at 1km resolution versus "observed" events for 2000-2019 at 30m resolution. MoFuSS patterns result unrealistic given the coarse resolution used in this study.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Note: A proper comparison would require similar periods but falls beyond this report. Although deforested areas for similar time periods are roughly the same, 1km^2 patterns are forced to be aggregated due to pixel resolution. Simulated deforestation in MoFuSS is expressed as the wood that becomes available after land is cleared

Appendix 3. Responses to public comments

1. As was mentioned previously, the CDM received 50 submissions from various stakeholders with nearly 300 individual comments, critiques and suggestions. After a detailed review, duplicate or closely related submissions were combined into a TECHNICAL REPORT that synthesizes and paraphrases each comment for easy readability and flow of information.[20] The submissions were then grouped into 10 thematic categories:[21]
    1. General Comments
    2. Tool30: Revisions, Clarifications and Proposed Changes
    3. MoFuSS Model: Uncertainties and Complexity
    4. MoFuSS Model: Improvements and Suggestions
    5. Account for Non-Residential Wood Fuel Demand
    6. Wood Fuel Consumption Data
    7. Biomass Stock and Growth Functions
    8. Location-tailored fNRB Values and Demand Scenarios
    9. Review, Validation & Verification Processes
    10. Transition Timelines, Validity Period and Updating Process

2. In this appendix, we review each thematic category and explain how the most salient comments were addressed.

1. General Comments

3. This section contained a mix of comments, which we list below, with our response in parentheses (): including:
    - several complaints that the CDM allowed insufficient time for the review and requests for extension (these requests were granted)
    - request for trainings (this is possible, but outside the scope of this assignment)
    - requests for clarification on technical points like how to interpret "pixel-scale fNRB", "woodfuel-shed", IDW algorithms (text was added to this report to clarify these details, though these details are quite technical so we refer interested readers to the peer reviewed scientific publications listed in the Section on "**Key background reading**")
    - requests to allow the use of Tool30 as an alternate approach to estimating fNRB (addressed in the next section)
    - include carbon sequestration in the methodology to assess emission reductions (this would require an entirely different methodology than those currently used for woodfuel projects. While this possible, it is beyond the scope of this assignment)

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[20] The Technical Report notes that during the review process, some information in the original submissions may have been omitted or incorrectly interpreted. Readers are encouraged to consult the full compilation of submissions to see the original comments.

[21] The Technical Report listed an 11th category, "Current Work", but that did not include any comments and is not addressed in this Appendix.

- guidance to PDs on identifying the relevant “project area” (while this is important, we consider this an issue that should be addressed by standards bodies, methodology developers, and the methodology panel).

2. Tool30: Revisions, Clarifications and Proposed Changes

4. This section contained a mix of comments directed at Tool30 including:
    - Several comments noting the assertions made in the report that accompanied the October 2023 release of preliminary fNRB estimates for SSA concerning Tool30’s shortcomings were inaccurate such as:

Comment	Response
the assertion that TOOL30 lacks provisions for explicit spatial analyses is inaccurate. In practice, the tool allows for survey data to be used.	First, survey data is not inherently spatial. Second, while Tool30 can, in theory, accommodate spatial data, it does not encourage or even hint that such data should be used. The words "map" or "spatial" do not appear anywhere in the text of Tool30. In this document, on p. 12, we state “Tool 30 provides guidelines for calculating fNRB without using explicit spatial analyses” and we believe this statement is justified.
The claim that the tool recommends using outdated 2000 FAO tree cover data that overlooks trees outside of forests that are harvested for fuelwood is incorrect. The tool, in fact, offers multiple sources for tree cover data and mandates the use of the most recent data.	The 2000 FAO GFRA is the **only source of data on forest area** explicitly mentioned in Tool30 that includes information about different forest cover types. That information is needed to effectively apply the IPCC’s 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. While other sources certainly could be used, none are suggested in Tool30. Moreover, while Tool30 states “The most recent available data shall be used” in the very next sentence, it states “the vintage of the above data shall not be before year 2000”, which clears a path for PDs to use the only source of data mentioned, FAO’s 2000 GFRA. Hence, we stand by our assertion.
The claim made by the Information Note (CDM-MP92-A07) that the CDM TOOL30 solely addresses accessibility by excluding protected areas from biomass supply consideration is inaccurate. The tool indeed encompasses and provides guidelines for defining geographically remote areas, considering factors like proximity to roads and rivers.	We agree with this statement - TOOL30 does accommodate “geographically remote areas” and suggests that PDs define these areas as anything "beyond the average distance travelled to collect fuelwood". We changed the description on p. 12. However, this has no impact on the results of the model.

- Other statements asked for clarification about the use of Tool30 for future projects including an assertion that more recent land cover data and better guidance on age-based MAI would result in more accurate fNRB estimates (we agree in theory, but identifying the most appropriate set of parameters is challenging – we explain this in revised text on p. 12.)
- Two submissions suggested that TOOL30 be disallowed rather than modified to result in more conservative/accurate values (we agree, if there is no significant effort put into developing better guidelines mentioned in the previous bullet point).

3. MoFuSS Model: Uncertainties and Complexity

5. This section contained comments noting the complexity of the model and the number of variables required. Some comments asked for clarification on key inputs and others suggested that the team adopt different approaches. We summarize the most salient of these comments in the bullet points below.

3.1 Lack of accounting for soil carbon (SOM) and dead organic matter (DOM)

6. Including these carbon pools would make an already complicated model much more complex. It is well beyond the scope of the assignment and would not have any impact on current carbon accounting for woodfuel projects because none of the woodfuel methodologies include SOC or DOM.

3.2 Use more localized project-based data

7. Several suggestions requested that MoFuSS include differences in country consumption or use more localized, project-base data to improve accuracy. MoFuSS is designed to use localized data; however, for this assignment, CDM requested estimates of fNRB at a global scale. It was not practical or possible to use local or project-specific data when modeling at this scale.

3.3 Wood-charcoal conversion factors

8. This and other sections asked for clarification of our sue of wood-charcoal conversion factors and how it compares with relevant literature. We offer an explanation on p. 11 of this document and include a citation to a peer-reviewed study of charcoal production.

3.4 Technical aspects of the model

9. There were several questions about specific aspects of the model code including whether we accounted to potential collinearities of input variables and the models use of predicted data (specifically for population and AGB). On the question about collinearity, we do account for collinearity of input variables. There are multiple Dinamica scripts for the case of MODIS and Copernicus configurations respectively.[22] However, collinearity is only relevant for regression analysis, which are not used in the large-scale regional model presented here (as explained in **Appendix 2**). Therefore, concerns about collinearity do

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[22] Access the scripts at these links:
https://gitlab.com/mofuss/mofuss/-/blob/master/linwin/scripts/LULCC/LULCt1_c/5_Correlation_gain_win241.egoml
https://gitlab.com/mofuss/mofuss/-/blob/master/linwin/scripts/LULCC/LULCt1_c/5_Correlation_loss_win241.egoml
https://gitlab.com/mofuss/mofuss/-/blob/master/linwin/scripts/LULCC/LULCt2_c/5_Correlation_gain_win241.egoml
https://gitlab.com/mofuss/mofuss/-/blob/master/linwin/scripts/LULCC/LULCt2_c/5_Correlation_loss_win241.egoml

not apply (though they can be addressed for any national or subnational MoFuSS model using prospective landscape simulations).

10. On the question about the use of predicted data, we stress that our baseline populations, population distributions, and AGB are taken from published and peer reviewed data sources. We predict the future evolution of these variables – all forward-looking analyses require prediction – but the base years for each variable are based on empirically measured, peer-reviewed sources of data.

3.5 Uncertainty

11. There were several questions about uncertainty in the model and its relationship to the "conservativeness" of the assumptions. We have added a section to this report explaining how we estimate uncertainty (see **Table 5** and accompanying text). However, uncertainty and conservativeness are not the same. Uncertainty can be quantified, while conservativeness is a subjective concept. We do not provide an estimate of how conservative the default values are.

3.6 Differences with WISDOM results from 2015

12. One comment highlighted the large differences and poor correlation between the results of the WISDOM-based analysis published in 2015 based on data from 2009 and the assessment released on October 2023, which was presented in the October 2023 report. We updated that discussion including the full national dataset (see **Figure 21**). The results still show poor correlation. There are several reasons for this. While the underlying concepts of the WISDOM and MoFuSS models are similar, the input data vary substantially. For example, as shown in **Figure 21**, our estimates of woodfuel consumption are only moderately correlated with the estimates from the 2015 study. In addition, inputs for the supply module such as AGB maps and growth rates differ substantially. When the work was for the 2015 study was conducted, there were no publicly available maps of pan-tropical AGB.[23] To estimate AGB, the WISDOM model imputed it from qualitative land cover maps and regional ecological zones. MoFuSS relies on peer-reviewed satellite-based observations of AGB that vary from the AGB estimates use for MoFuSS. These differences also result in different biomass growth rates, because those are derived from AGB stocks.

4. MoFuSS Model: Improvements and Suggestions

13. Comments in this section ranged from concerns about stove/fuel stacking, openness of the model and standardization of input data, accounting for sources of deforestation and land use change, future changes in transportation networks, alternate sources of AGB data, national borders, and urban fNRB. We discuss each of these points briefly below.

4.1 Stove/fuel stacking

14. Several comments raised concerns that our failure to account for stacking could lead to underestimates of fNRB. The reason that stacking was not included in the model is that there is very little nationally representative data so that the team had very little information to work with.

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[23] The maps of 2010 AGB used in this assessment were not published until 2018-2021.

15. However, we stress that it is impossible to state *a priori* whether excluding stacking leads to underestimates or overestimates of woodfuel demand. We calculate total woodfuel consumption by multiplying the number of primary fuel users by per capita fuel consumption. The population of primary fuel users includes both exclusive users and people who stack. Using urban Uganda in 2020 as an example, our data looks like this:
    - 4 million primary fuelwood users who use 0.4 oven-dry tons of wood per person/year
    - 7 million primary charcoal users who use 0.16 tons of charcoal per person/year
    - 0.1 million primary LPG user who use 50 kg of LPG per person/year

16. The charcoal group probably includes people who cook some of their meals with LPG or fuelwood and use less than 0.16 tons of charcoal per year. This would result in overestimates of charcoal consumption and fNRB. The LPG and fuelwood groups probably include some people who cook with charcoal and use less than the stipulated amount of wood and LPG. They are not counted in our model, resulting in overestimates of wood and LPG, and underestimates of charcoal consumption. We do not have enough evidence to say decisively if the overestimate of charcoal consumption among the charcoal group outweighs the underestimate of charcoal consumption in the wood and LPG group. This depends on the relative size of the three groups and the extent to which one fuel displaces others.

17. We would need to do additional research and analyses to quantify this for any country, which was beyond the scope of this assignment. In addition, the results from any one country would not necessarily be generalizable to others.

4.2 Openness of the model and standardization of input data

18. One comment requested that we ensure that the model is open and any methodologies align with this modelling approach but still allow projects to use their own inputs. Currently, the model is completely open in that all software and code is freely available and can be run. with adjustments to key inputs like fuel consumption. However, it is a complicated model and requires some knowledge of coding in the appropriate languages (R, C++, and Dinamica-EGO). We are in the process of developing an open-access cloud-based version of the model, which will allow anyone to run it for an area of interest (country, project area, etc) and adjust parameters without needing to download software or understand the underlying code. However, this is not part of the current assignment and is not yet fully-funded so the timeline of this output is uncertain.

4.3 Accounting for sources of deforestation and land use change

19. At least one comment suggested that because we cannot use the MoFuSS module that simulates agricultural expansion or other sources of deforestation when modeling at this scale, we should use an adjustment factor to increase fNRB values as compensation. While we understand the motivation here, this raises problems because very few countries are affected in the same way. Also, deforestation dynamics often lead to lower fNRB values because a significant portion (40% by default in MoFuSS) of woody residues from land clearing are used as woodfuel during the year. These residues do not contribute to NRB as they originate from other drivers. In areas with ongoing deforestation, these residues can meet a substantial part of the woodfuel demand. As woody biomass sources are being cleared, people will tend to walk/drive farther, but this do not affect NRB neither.

4.4 Future changes in transportation networks and urban areas

20. Several comments suggested we include future changes in roads and urban populations. For road networks, this would require prospective modeling that is well beyond the scope of this study. In addition, while the link between roads and deforestation in global hotspots like the Amazon region is well-established, the impact of roads and woodfuel-driven degradation is much more tenuous.

21. Other comments suggested that we adjust the spatial distribution of urban areas by coding rural areas as urban when they pass the "urban threshold" of population density. While there is a certain logic to this, we already account for growth in the size of the urban population by using UN urbanization forecasts. If we also allowed rural areas to transition into urban, then we would be overestimating the total urban population.

4.5 Alternate sources of AGB and biomass growth data

22. Several comments suggested we consider alternate sources of AGB and biomass growth data. Some comments reflect a misunderstanding of what the model actually does. For example, one comment "strongly" recommended that we use AGB growth rates from IPCC's 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories specific to the respective age category and that we source various forest age categories from the host countries. We have two responses to this. First, we do use the IPCC's data for r_{max}, but as we explain in the "2.6 Biomass growth functions" section, we use the value assigned to young stands (< 20 years) as one parameter in a logistic function, which ensures that the other values (> 20 years and "primary forests") are also applied when the tree cover is at that stage. However, the suggestion to use host country data to determine forest age categories, is simply unrealistic. National forest inventories do not track stand ages except in managed plantations. In unmanaged landscapes, disturbances are usually spatially heterogeneous leading to mixed-age stands. We use AGB stock as a proxy for age, and assign growth rates based on stock, rather than age.

23. Other comments suggested we consider alternate sources of ABG including GEDI. We explored the use of GEDI data and spoke with GEDI developers. Our interest in GEDI was not as a baseline AGB map, but as a way to calibrate simulated AGB losses. After some exploration, we found GEDI is not ready for this application but agreed to discuss future collaboration with the GEDI team.

24. The same commentor suggested that we calibrate and validate MoFuSS outcomes "against real AGB estimates and patterns of deforestation". This is beyond the scope of this CDM assignment, but we are currently exploring collaborations with researchers who work with high resolution tree cover data. This work is ongoing and we will make adjustments to the model based on the outcome of these analyses if necessary.

4.6 National borders

25. Several comments noted that the model should be rerun with all Sub-Saharan Africa in one unit to properly account for cross-border trade. We had intended to do this; however, as we explain in the main body of the report, this was not possible. The model simply could not handle the level of detail required to simulate the wood harvesting demands from 3.3 million populated pixels ranging over 24 million square kilometers of SSA. In addition, though the model is fully functional with small clusters of 3 or 4 countries, we underestimated the degree to which we'd need to calibrate our assumptions about transborder trade. As we explain in the main text, applying uniform "friction" at international boundaries to every border resulted in some trade flows that seemed reasonable and others that did not, including some that

contradicted observations on the ground. As a result, we decided to cluster some countries and keep others isolated.

4.7 Urban fNRB

26. Please see the section “2.15.5 Assigning fNRB to urban **locations**” on p. 255 of the revised report.

5. Account for Non-Residential Wood Fuel Demand

27. Comments in this section focused on the need to include non-residential sources of woodfuel consumption. These sources include commercial entities like restaurants and hotels, educational and government institutions, and cottage industries like brick burning, beer brewing, and agricultural processing. These sources of woodfuel consumption were originally omitted because there is very little reliable data covering most countries included in the analysis. However, this led to systematic underestimates of national woodfuel consumption for many countries where non-residential sources can be significant. This was addressed by considering data from a small number of studies and adjusting fuelwood and charcoal consumption in all countries based on those data. This is fully explained in the revised report on p. 12.

6. Wood Fuel Consumption Data

28. Comments in this section focused on the CDM default value of annual per capita wood consumption in SSA. Additional comments in this section included concerns thar the assumptions used to estimate wood harvesting in protected areas were inaccurate and should rely on “proper survey data, assumptions about friction be allowed to vary depending on factors like safety/rule of law, human development, or economic growth, and a suggestion that the team consider generating different values of fNRB for firewood and charcoal.

6.1 Annual per capita wood consumption

29. Nearly all commentors consider the CDM default of 0.4 tons per capita too low. Other comments included requests to allow PDs to use data from their own surveys or KPTs, or collect nationally approved data from host governments. Several commentors suggested that the MoFuSS team rely on “Host Country approved DHS or Census data”. This last comment, which was repeated several times, reflects a misunderstanding of the data in those sources. DHS and censuses are excellent sources of nationally representative data about primary fuel choice. The WHO uses these datasets to generate their time series forecasts, which are used in MoFuSS. However, **DHS and Census data have no information about the quantities of fuel consumed**.

30. We addressed these comments by increasing per capita consumption in SSA and applying different regional defaults to other regions. See the discussion on p. 12 of the revised report.

6.2 Wood harvesting in protected areas

31. While it is certainly true that access to protected areas for woodfuel extraction varies within and between countries, implementing surveys to accurately capture this data in multiple countries is well beyond the scope of the current assignment.

6.3 Adjusting friction based on country-level social and political indicators

32. Friction maps represent the ease or difficulty with which wood harvesters move across the landscape. While it is true that ease of physical movement can be corelated with governance, the magnitude and direction of influence that things like rule-of-law and economic growth have on ease of movement is not obvious and would need to be empirically determined. For example, does better governance impede or ease movement? On one hand, better governance might ease access to wood for harvesting because people follow rules and regulations and police do not demand bribes at forest boundaries and road checkpoints. On the other hand, better governance might impede movement because rules governing tree harvesting and charcoal transportation are fully enforced, making access and transport more difficult. These are interesting questions, but unfortunately cannot be addressed within the scope of this assignment.

6.4 Differing fNRB for firewood and charcoal

33. Several suggested doing separate analyses for fuelwood and charcoal. These comments also appeared in other categories. We address all such comments here. While it is possible to carry out separate analyses for wood and charcoal, MoFuSS assesses fNRB as the joint impact of fuelwood and charcoal harvesting together, which is additive. Separating them into different models would result in lower fNRB estimates for both fuel pathways.

34. We understand that these comments stem from a concern that our assessment is not capturing the larger impacts that charcoal has relative to harvesting fuelwood. However, this is captured indirectly because the default fuel consumption values we use assume that people cooking with charcoal harvest 2.4 times more wood for their cooking needs than people using fuelwood. Therefore, charcoal interventions achieving a given reduction in demand should achieve larger emission reductions than similarly designed fuelwood interventions.

7. Biomass Stock and Growth Functions

35. Comments in this category focused on requests that the AGB maps undergo some validation and concerns about overestimation of biomass regrowth as well as requests that for clarification of certain terms.

7.1 Validation of AGB maps

36. These comments noted that the AGB maps used in this assessment require validation and that the report include information about the model's ability to accurately predict future AGB. We have noted in the revised report that the assessment used the NASA dataset, not WCMC as October 2023 report the erroneously stated. The NASA dataset has undergone extensive validation, and its strengths and weaknesses are well understood in the scientific community. We have included citations in the main text so commentors can review the original sources themselves.

37. Comments also requested that we provide information about the model's accuracy in predicting future AGB values. While we understand the desire for predictive accuracy, it is difficult to compare MoFuSS future projections to future changes in tree cover (the future hasn't happened yet). However, it is possible to run MofuSS over a past time period and compare the model's predicted tree cover change to observed tree cover change. However, the CDM terms of reference did not include time or budget for this validation

exercise. The MoFuSS team intends to undertake such an exercise in the near future as soon as a funder can be identified to cover the necessary work.

7.2 Overestimation of biomass regrowth

38. This comment referred to a section in the October 20203 report that noted if we used the IPCCs default values for maximum stocks of woody AGB, our simulations could overestimate regrowth and underestimate fNRB. However, we do not take that approach. Rather, we use NASA's AGB maps to define maximum woody tree cover based on ecological zone and LULC category as explained on pp.9-10 and shown in **Table 1**.

7.3 Clarifying terms

39. Commentors requested that we clarify "maximum AGB stocks" and "growth rates (r_{max})" and to indicate whether our the AGB maps and equations used include all biomass or only woody biomass. We have provided detailed descriptions of maximum AGB stocks (symbolized by "K") and r_{max} in the report. In addition, we have made it clear that AGB maps and equations refer only to woody biomass.

8. Location-tailored fNRB Values and Demand Scenarios

40. The comments in the category noted the need for clarity on national vs/ subnational fNRB defaults, providing "ranged guidance" like an upper bound of fNRB that can be used, requests that the analysis be extended to other world regions, and accuracy of fNRB values. There were also requests already noted in previous sections that fNRB should be disaggregated to highlight differential impacts between fuelwood and charcoal.

8.1 Clarity on national vs/ subnational fNRB defaults

41. Some of the comments focused on spatial variability of fNRB and the need for guidance on the use of national vs. sub-national values. One comment suggested only allowing default values at one admin level, to prevent developers from picking among the most advantageous values. Other comments suggested allowing country authorities to decide their own default values, and one comment surprisingly suggested using "Using a globally uniform fNRB default value". We respond to these comments by stressing both the previous and the current assessment included fNRB estimates at national and two sub-national administrative levels. The report includes national values and sub-national values are available at links provided in the main report. However, it is difficult to provide generalized guidance about which values are most appropriate because it depends on the specific context. Some projects are highly localized and the 2nd admin level might be most appropriate. Others are national in scope and should account for fNRB in most or all administrative units.

42. On the comment that country authorities decide their own default values, we recognize and respect the that national sovereignty is paramount on these issues. However, we also caution that previous national defaults were derived using unreliable methods and were unrealistically high. In addition, some contradicted national data generated and published by the same government authorities. For example, between 2012 and 2017, [Uganda used a national default fRNB of 82%](). However, in 2015, the Ugandan Ministry of Energy and Mineral Development released a national [Biomass Energy Strategy (BEST)]() in which national woodfuel consumption was estimated to be 44 million tons/year while the sustainable accessible

wood supply was estimated to be 26 million tons per year. This implies that by the Ugandan government's own estimates, consumption exceeded sustainable supply by approximately 18 million tons, resulting in a national fNRB of 18/44 = 41%. Unfortunately, the assessment from the BEST had no bearing on the "official" 82% default.

8.2 Ranged guidance

43. This comment asked for guidance on the upper bounds of fRNB that can be used understanding that there is spatial variation around any given point. Each admin level that we report represents a spatial average of fNRB within that boundary. Though we make pixel-based raster maps available for download, we advise against using pixel-based values or taking spatial averages below the second admin level. Few projects operate at such local scales and fNRB assessed at 1km resolution can be misleading when looking at small localities because localized details are omitted.

8.3 Extension to other world regions

44. The October 2023 release focused on sub-Saharan Africa. All world regions where traditional woodfuels are used are included in this updated assessment.

9. Review, Validation & Verification Processes

45. The comments in this category requested either validation of the key input data used, which was already addressed in previous sections, or validation of the fNRB values generated through this assessment. Other comments requested that fNRB be defined or adapted on a project-specific basis or generated using field-collected data "to enhance the precision of the results".

9.1 Validation of fNRB values

46. As we noted in previous sections, validation was not included in the ToR for this assessment; however, the MoFuSS development team is currently discussing ways to validate the key assumptions and results. If, through this process, we discover substantial inconsistencies between observed impacts and impacts that are projected by MoFuSS, then we will adjust the model. However, stakeholders should be aware that validation might lead to downward, rather than upward adjustments in fNRB. In addition, the MoFuSS team stresses that fNRB is not a directly observable quantity in the same sense that changes or degradation of tree cover are directly observable. As such, are no "true" values of fNRB to against which MoFuSS results can be compared. Instead, validation will entail comparing direct observations of changes or degradation of tree cover and quantifying the possible role of woodfuel demand on those changes. In addition, we should note that previous estimates of fNRB derived from Tool30 or other recommended methodologies have not undergone any external validation.

9.2 Project-specific fNRBs and use of field data

47. There were numerous comments suggesting that methodologies allow PDs to estimate project-specific fNRB values, potentially using field-data as inputs. As we explained in other sections of this response, MoFUSS developers are working on a cloud-based version of MoFuSS that will allow PDs to develop their own models using their own inputs, which could be based on government data or data derived from field measurements.

10. Transition Timelines, Validity Period and Updating Process

48. These comments focused largely on procedural issues like the timeline for completing the current assessment, the period for which the new fNRB estimates will be valid, and a request for guidance on transitioning from previous fNRB values to the current approach. These comments can not be addressed by the MoFuSS developers and have been forwarded to the CDM MP.