CLEAN DEVELOPMENT MECHANISM

CDM-MP92-A07

Information note

Development of default values for fraction of non-renewable biomass

Version 01.0

United Nations
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Climate Change

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1. Procedural background

1. The Executive Board of the clean development mechanism (CDM) (hereinafter referred to as the Board), at its 116th meeting, considered the information on development of accurate and reliable region-specific default values for fraction of non-renewable biomass (*fNRB*) that can be applied in methodologies for clean cooking and requested the MP to develop subnational/regional values of *fNRB*, building on scientific studies and engaging external experts. The Board highlighted that such default values should be consistent with the methods contained in "TOOL30 Calculation of the fraction of non-renewable biomass". In this regard, the Board requested the Methodologies Panel (MP) to prepare a concept note based on the work undertaken for consideration by the Board at a future meeting. The Board further requested the MP to propose a revision to TOOL30 and/or related methodologies/tools if there is a need to further clarify and/or revise elements of TOOL30 or related methodologies/tools, in light of the work undertaken on default values.

2. Purpose

2. The purpose of this information note is to address the mandate provided at EB116 (i.e. develop subnational/regional values of *fNRB*) and inform the Board of the advancement of this task.

3. Key issues and proposed solutions

3.1. Existing approach to calculate *fNRB*

3. CDM programmes of activities (PoAs) have a high share of efficient cookstove projects which reduce consumption of non-renewable biomass. The *fNRB*, as opposed to what can be sustainably harvested, is one of the key parameters for calculating emission reduction in the methodologies for efficient cookstoves such as “AMS-II.G. Energy efficiency measures in thermal applications of non-renewable biomass”, along with other parameters such as the annual consumption of woody biomass and efficiency of devices.

4. In accordance with “TOOL30: Calculation of the fraction of non-renewable biomass” for estimating *fNRB*, project participants currently have three options when determining *fNRB* values: (a) Using a default value of 0.3; (b) Using pre-approved default country-specific values, known as the standardized baselines, where available; or (c) Calculating project specific *fNRB* values using TOOL30.

5. The current default value of 0.3 that can be applied globally was adopted by the Board at its 97th meeting as a conservative default, taking into account literature available at that time[1].

6. Over time, it became apparent that this universal default value of 0.3 has seldom been applied in CDM projects and PoAs. Instead, most projects used either of the other two options which yielded much higher and therefore less conservative values of the *fNRB*. In

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[1] For example, Bailis, R.; Drigo, R.; Ghilardi, A. & Masera, O. (2015). The carbon footprint of traditional woodfuels. Nature Climate Change, 5(3), pp. 266–272. This paper estimated that global *fNRB* value was 27 to 34 per cent, with large geographic variations.

addition, the data used to establish that default value, by now over a decade old, are likely to be outdated as well as some of the data is based on very limited study and anecdotal reporting.

7. In that context, the EB116 requested the MP to develop subnational/regional values of *fNRB*. External experts have been engaged to assist the work of the MP on this matter. The draft report of the external experts is available in Appendix 2 of this document.

8. The sections below describe the approach used by the external experts to develop new default values of *fNRB*.

3.2. Approach to develop new default values of *fNRB*

9. The assessment of *fNRB* values was conducted using the latest available data on woody biomass supply and demand with the Geographic Information System (GIS) based model called MoFuSS. The model relies on the same basic concepts used by the Woodfuels Integrated Supply/Demand Overview Mapping (WISDOM) methodology, used to derive the results on which the current default value of 0.3 is based, with several key differences. Where WISDOM uses a snapshot in time, the MoFuSS model runs simulations, which allow users to compare intervention (i.e actions to reduce extraction on non-renewable biomass such as through efficient cook stove projects) and non-intervention scenarios that incorporate dynamic variables such as population growth, urbanization, and land cover change.

10. In the first phase of the assessment, the model was run for 43 countries in Sub-Saharan Africa. These countries/regions were selected as they account for the large majority of CDM projects and PoAs in the pipeline. Subject to guidance from the Board, work will continue to be conducted for the remaining countries/regions in the world; with the possibility of further updates given new global datasets and assumptions become available in the coming years.

11. There are similarities and differences in the approach used in the assessment and the approach defined in TOOL30. For example,

    (a) While TOOL30 defines biomass consumption on a jurisdictional basis (e.g. districts, counties, or countries), **the model used in the assessment calculates it at pixel level (tons of dry biomass per hectare or km^2) and then uses this data to derive results at larger aggregation levels;**

    (b) Though both TOOL30 and the MoFuSS use biomass growth parameters such as Mean Annual Increment (MAI) and Current Annual Increment (CAI) respectively, to define long-term average wood growth, in case of TOOL30 biomass growth parameters are applied to the entire land cover categories regardless of their conditions. In contrast, **the new model relies on growth functions**, which are specific to land cover type and ecological zone, and vary with current stock levels. The model applies these functions at the pixel level, so that every pixel has a unique woody biomass production function. Therefore, it is expected that the model simulates biomass harvest and regrowth after harvest more realistically;

    (c) TOOL30 only considers accessibility in the sense that it removes protected areas from consideration of biomass supply. MoFuSS also accounts for protected areas but goes further by considering physical accessibility based on topographical features and the effort that woodfuel users must expend to access sources of woody biomass.

12. In this assessment, the following steps were taken to develop *fNRB* values:

    (a) Create maps of **woody biomass use** from 2010 to 2050, using population distribution maps, and woodfuel demand scenarios;

    (b) Create maps depicting **where the woody biomass from the previous step is coming from** (i.e., where it is being harvested and/or collected in each year), using accessibility functions that integrate recent globally harmonized maps of land cover, biomass/carbon stocks, roads, rivers, elevation, and protected areas; this is calculated for each and every single place using biomass;

    (c) Create maps of the **potential regrowth and/or replenishment of woody biomass** in natural and anthropic ecosystems respectively, after being harvested for fuelwood or charcoal;

    (d) Generate **maps of woody biomass harvest, NRB, and *fNRB*** between 2010 and 2050, at both the pixel and administrative level.

3.2.1. Estimation of woody biomass supply and accessibility

13. Biomass stocks 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. Among the several global maps of above-ground biomass available that could be used in the model, the dataset provided by the World Conservation Monitoring Centre (WCMC) was used. The map shows above- and below-ground carbon stocks in tonnes per hectare from 2010 and the resolution is 300m.

14. The biomass growth functions rely on two important parameters: annual growth rate and maximum stock within each pixel. The specific growth functions were used to simulate woody biomass growth in each pixel by land-cover type and ecological zone.

15. The model focuses on stocks and growth rates of above-ground biomass, 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 model does not account for changes in SOC and only addresses DOM indirectly.

3.2.2. Estimation of current and projected demand for woodfuel

16. Both current and future biomass consumption are contributors to *fNRB*. Spatial modelling of the impacts of biomass consumption requires the estimates of the quantity consumed and the location of consumers. To estimate the quantity of fuelwood and charcoal consumed, the model relied on two simple parameters**: the number of users and the amount per user.** The number of fuelwood 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.[2]

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[2] World Health Organization. "Household Air Pollution Data." Air pollution data portal, 2021. https://www.who.int/data/gho/data/themes/air-pollution/household-air-pollution.

17. The model focuses primarily on residential woodfuel demand. In some countries, wood may be consumed by formal and cottage industries as well as commercial establishments. The model does not include these sources of demand for several reasons: first, because there is no reliable data for the use of wood by cottage industries and informal such as brickmaking, fish smoking, beer brewing; second, while FAO publishes data on industrial roundwood production, in most countries in sub-Saharan Africa, this accounts for less than 10% of the overall wood harvest.[3]

18. Accessibility to woody biomass was also accounted for by defining “friction” maps that represent the effort that wood consumers must expend to travel to a given supply area. These maps are derived by integrating road and river networks, land cover characteristics, elevation, and protected areas.

3.2.3. Other considerations

19. Use of deforestation by-products: There are very few studies that have measured the share of woody biomass cleared for agriculture that is used as firewood or charcoal. In this assessment, it is assumed that 70% of the woody by-products of land clearance is accessible in a given year, but that it is only available that year. This assumption has a small impact on the overall results but may have a significant impact on *fNRB* estimations being conservative in locations that experience high rates of tree cover loss in densely populated areas. When running the model for this study, this function was not activated because the algorithms used were not effective across very large regions.

20. Treatment of Protected Areas: 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.

21. National boundaries and trade: The sustainability of woodfuel consumption within national boundaries can be affected by transboundary trade. For example, if woodfuel is imported to Country A from neighbouring Country B, it relieves pressure on domestic sources of woody biomass in Country A, but increases pressure on domestic sources of woody biomass in Country B. The MoFuSS model can accommodate transnational trade; however, it is difficult to model because there is no reliable data to verify the results. In addition, for this analysis, Africa was divided into four sub-regions (East, Central, Southern and West) to reduce the computing time necessary for each modelling run. Thus, while transborder trade could occur between countries within each region, it could not occur between countries in separate regions, even if they share a common border such as Chad

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[3] This is based on a comparison of FAO industrial roundwood production data and residential woodfuel consumption. FAO data is from FAO Statistics Division. “FAOSTAT.” License: CC BY-NC-SA 3.0 IGO. Forestry Production and Trade, 2023. https://www.fao.org/faostat/en/#data/FO.

and Niger or Cameroon and Nigeria, because they were modelled separately. Modelling the entire SSA region in one simulation will be carried out in the near future.

3.3. Results of *fNRB* values

22. *fNRB* is defined at the pixel level for a given time period as:

$$fNRB_{(t=n),j} = \frac{NRB_{(t=n),j}}{H_j} \quad \text{Equation (1)}$$

Where:

$fNRB_{(t=n),j}$ = Fraction of non-renewable biomass (fraction or %) in pixel *j* during the simulation period of “n” years

NRB_j = Quantity of non-renewable biomass harvested in pixel *j* during the simulation period of “n” years

H_j = Total consumption of woody biomass in pixel *j* during the simulation period of “n” years

And

$$NRB_{t=n,j} = \begin{cases} 0 \; if \; AGB_{t=n,j} \geq AGB_{t=0,j} \\ AGB_{t=n,j} - AGB_{t=0,j} \; if \; AGB_{t=n,j} < AGB_{t=0,j} \end{cases} \quad \text{Equation (2)}$$

Where:

$AGB_{t=0,j}$ = Above ground woody biomass in pixel *j* in the initial year of interest

$AGB_{t=n,j}$ = Above ground woody biomass in pixel *j* in the final year of interest

23. The model simulates the supply and demand for the period 2010 – 2050. This is used to estimate the *fNRB* values, which can be defined for the entire simulation, or divided into smaller time periods. This information note presents the *fNRB* results for the period 2020 – 2030 only.

24. To be applied 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 in each pixel during the simulation period and divides that by total consumption during the same time period within the same boundary.

$$fNRB_{(t=n),project\ area} = \sum\nolimits_j NRB_{(t=n),j} \Big/ \sum\nolimits_j H_j \quad \text{Equation (3)}$$

25. Where “project area” is shorthand for a country, sub-national administrative boundary, or any project-specific geographic boundary and NRB_j, H_j, “t=n” are defined above and j indicates all the pixels in the “project area”.

26. Figures 1, 2 and 3 below illustrate spatial averages of *fNRB* by national and sub-national administrative (the first administrative level and the second administrative level)

boundaries for 43 countries in Sub-Saharan Africa. Table 1 in appendix 1 shows a summary of results at the national level.

27. The results of this analysis will also be displayed on a freely available website that will allow project developers to select and generate spatially averaged results for any project activity or PoA boundary.

Figure 1. ***fNRB*** **values at the country level for the period 2020-2030**

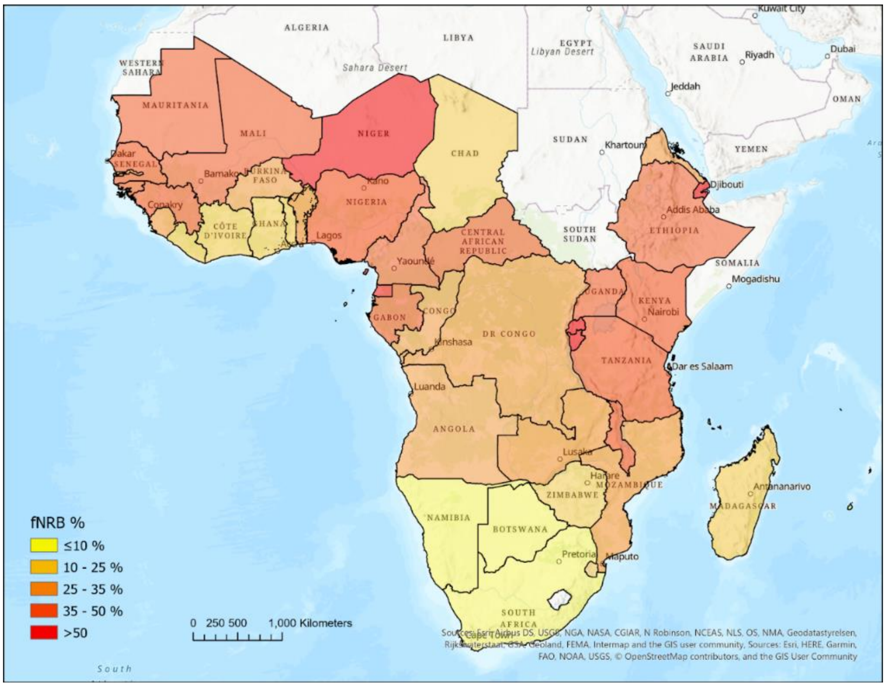


Figure 2. ***fNRB* values at the first administrative level for the period 2020-2030**

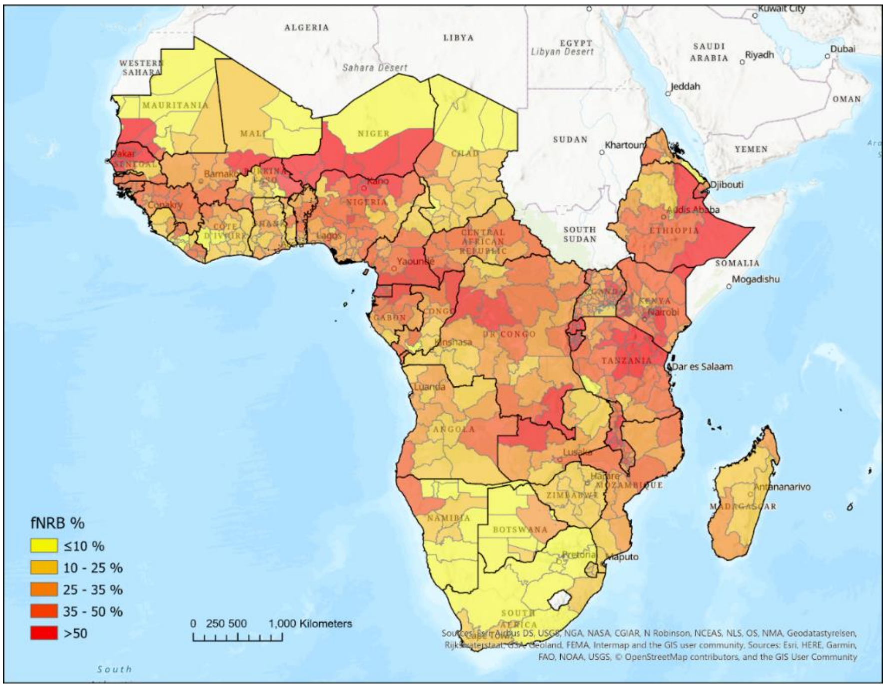
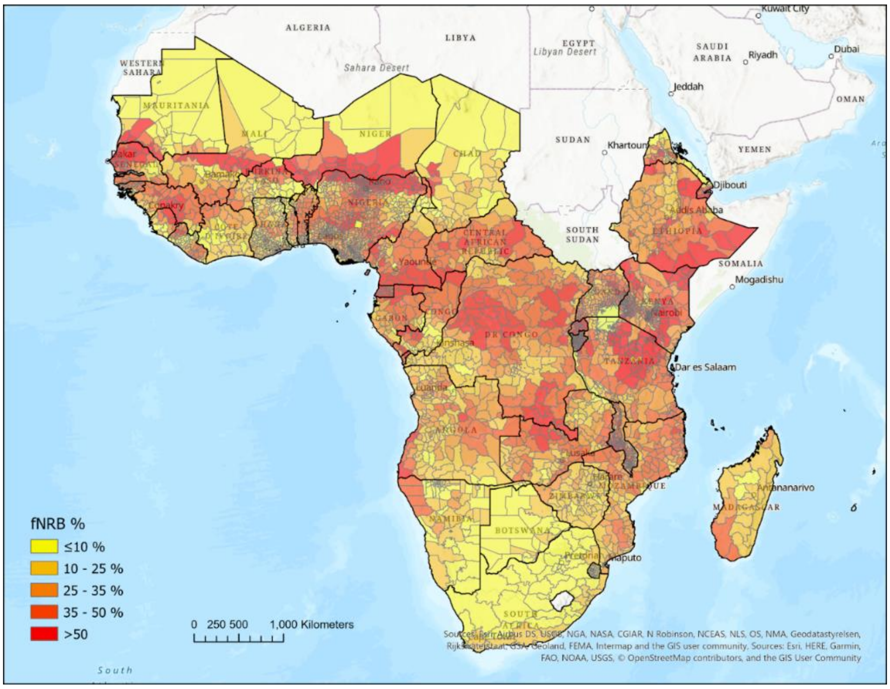


Figure 3. ***fNRB* values at the second administrative level for the period 2020-2030**



28. In some countries, there is high variability of *fNRB* across different administrative units. Tables 2 and 3 of Appendix 1 provide subnational *fNRB* values for the Republic of Congo and Mauritania respectively. The variability arises for similar reasons though the geographies are very different. Both countries have sub-national units with large

differences in population density and accessibility. So, we see high NRB close proximity to populated regions and low NRB in the unpopulated regions.

29. The external experts also conducted preliminary analyses in Central America, South Asia and Southeast Asia and presented results for those regions. These are shown in Table 4 of Appendix 1. These results should be considered preliminary. More analyses are forthcoming, which will result into national and sub-national values for each region.

4. Impacts

30. National/subnational/regional values of *fNRB* will ensure the reliability of calculating emission reductions, reduce transaction cost and facilitate the implementation of CDM project activities and PoAs in the household cookstove or water purification sector.

5. Subsequent work and timelines

31. The MP agreed to launch a call for public input on the approach adopted and proposal for improvement. Any inputs received will be considered by the MP for possible improvements to the work at its future meeting.

32. Subject to guidance from the Board, the MP will continue to develop default values for the fraction of non-renewable biomass for the other countries not covered in this document.

33. The MP will also continue to review the current requirements of TOOL30 and propose improvements through a revision to TOOL30.

6. Recommendations to the Board

34. The MP recommends that the Board take note of the information and provide further guidance.

Appendix 1. Values for fraction of non-renewable biomass

1. Country-level

35. Tables 1 below provides preliminary results of the *fNRB* values at the country level for 43 countries in Sub-Saharan Africa.

Table 1. *fNRB* values at the country level for the period 2020-2030

ID	County	Subregion	NRB (2020 - 2030)	Harvest (2020 - 2030)	*fNRB* (2020 - 2030)
1	Sao Tome and Principe	Middle Africa	0	26	1
2	Mauritius	Eastern Africa	1	20	6
3	South Africa	Southern Africa	1,939	24,662	8
4	Botswana	Southern Africa	198	2,316	9
5	Namibia	Southern Africa	287	2,799	10
6	Swaziland	Southern Africa	227	1,617	14
7	Comoros	Eastern Africa	30	183	16
8	Zimbabwe	Eastern Africa	10,261	55,465	18
9	Cote d'Ivoire	Western Africa	25,029	130,474	19
10	Chad	Middle Africa	14,101	74,540	19
11	Ghana	Western Africa	32,966	161,532	20
12	Madagascar	Eastern Africa	38,213	174,794	22
13	Liberia	Western Africa	9,612	42,372	23
14	Togo	Western Africa	9,559	40,834	23
15	Angola	Middle Africa	33,702	131,867	26
16	Burkina Faso	Western Africa	31,502	116,872	27
17	Republic of the Congo	Middle Africa	12,392	46,613	27
18	Eritrea	Eastern Africa	5,280	17,711	30
19	Sierra Leone	Western Africa	19,628	65,899	30
20	Gambia	Western Africa	2,523	7,811	32
21	Democratic Republic of the Congo	Middle Africa	223,304	694,673	32
22	Zambia	Eastern Africa	37,083	113,828	33
23	Mozambique	Eastern Africa	54,973	163,634	34
24	Benin	Western Africa	26,208	75,389	35
25	Cameroon	Middle Africa	36,066	100,829	36
26	Ethiopia	Eastern Africa	193,578	537,661	36
27	Mali	Western Africa	65,630	184,740	36
28	Central African Republic	Middle Africa	11,278	29,685	38
29	Uganda	Eastern Africa	108,732	288,867	38

ID	County	Subregion	NRB (2020 - 2030)	Harvest (2020 - 2030)	*fNRB* (2020 - 2030)
30	Nigeria	Western Africa	267,522	678,337	39
31	Mauritania	Western Africa	8,778	21,918	40
32	Guinea-Bissau	Western Africa	5,942	14,138	42
33	Guinea	Western Africa	67,842	161,787	42
34	Gabon	Middle Africa	1,047	2,418	43
35	Kenya	Eastern Africa	151,363	333,772	45
36	Senegal	Western Africa	35,611	79,600	45
37	Malawi	Eastern Africa	36,703	77,770	47
38	Tanzania	Eastern Africa	140,579	299,239	47
39	Equatorial Guinea	Middle Africa	1,309	2,404	54
40	Rwanda	Eastern Africa	33,856	57,078	59
41	Burundi	Eastern Africa	36,862	61,111	60
42	Djibouti	Eastern Africa	871	1,420	61
43	Niger	Western Africa	52,821	85,663	62

2. Subnational level (the first administrative level)

36. Tables 2 and 3 below provide preliminary results of the *fNRB* values at the subnational level for the Republic of Congo and Mauritania respectively, both of which show high variability.

Table 2. ***fNRB*** **values at the subnational level in the Republic of the Congo**

First administrative level	NRB (kt) (2020 - 2030)	Harvest (kt) (2020 - 2030)	*fNRB* (2020 - 2030)
Bouenza	458	4447	7
Brazzaville	1	40	2
Cuvette-Ouest	270	1027	21
Cuvette	1176	3742	26
Kouilou	1647	3671	38
Lekoumou	2621	5275	42
Likouala	1064	2013	45
Niari	1854	5737	27
Plateaux	1199	7779	12
Pointe Noire	0	9	0
Pool	1814	12288	11
Sangha	287	583	41
National Total	**12392**	**46613**	**27**

Table 3. *fNRB* values at the subnational level in Mauritania

First administrative level	NRB (kt) (2020 - 2030)	Harvest (kt) (2020 - 2030)	*fNRB* (2020 - 2030)
Adrar	0	115	0
Assaba	245	2498	12
Brakna	1542	2969	41
Dakhlet Nouadhibou	0	8	0
Gorgol	1617	2822	50
Guidimaka	979	2215	43
Hodh ech Chargui	748	3269	20
Hodh el Gharbi	451	2743	14
Inchiri	0	42	0
Nouakchott	0	33	0
Tagant	4	193	2
Tiris Zemmour	0	44	0
Trarza	3192	4968	54
National Total	**8778**	**21918**	**40**

3. Other regions (aggregated for regional values)

37. Table 4 below provide preliminary analyses in Central America, South Asia and Southeast Asia and presented results for those regions.

Table 4. Regional *fNRB* values for Central America, South Asia and Southeast Asia

First administrative level	NRB (kt) (2020 - 2030)	Harvest (kt) (2020 - 2030)	*fNRB* (2020 - 2030)
Central America	108721	355017	31
South Asia	1482834	5333689	28
Southeast Asia	618982	1551628	40

Appendix 2. Report from external experts

Updated fNRB Values for Woodfuel Interventions

Adrian Ghilardi and Rob Bailis

Final version, October 9th 2023

Contents

Introduction

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.

What is fNRB?

Trees grow naturally in many environmental conditions and wood can be considered a conditionally renewable resource [1]. For example, 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 measurement of the relative amount of wood that is harvested above the landscape's natural rate of regeneration.

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 CO_2 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.

How is fNRB used in carbon offset methodologies?

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 UNFCCC'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 ot 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.

Over time, both UNFCCC and voluntary methodologies were modified to remove some of the guesswork that characterized the first methodologies. In 2017, the UNFCCC 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.

The first Global fNRB Assessment

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].

Reassessing fNRB

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 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.

To fill the need for new default values, the UNFCCC 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.

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.

Key assumptions in MoFuSS

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 1 or 2 for a full description]. The list is divided into two sections. The first section describes the assumptions that are highly uncertain and/or associated with results that are very sensitive to small changes in input parameters. The second section describes other assumptions that are somewhat less critical but could still result in different outcomes if input parameters changed substantially.

Biomass stocks

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:

- World Conservation Monitoring Centre - this map shows above- and below-ground carbon stocks in ton per hectare for ~2010. The resolution is ~300m and the data has not undergone any validation.
- Woodwell Climate Research Center (formerly Woods Hole Research Center) - this map shows woody biomass density for tropical countries at 500m resolution for ~2012.
- NASA Global Aboveground and Belowground Biomass - these maps show biomass carbon density at 300m resolution for 2010
- GFW Live Woody AGB Density - this map shows aboveground 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).
- GlobBiomass - this map shows above ground biomass expressed in oven-dry tons per hectare at 100-150m resolution for 2010

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 that timeframe.

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 widely across different land cover types and sub-national administrative areas. Figure 1 shows the distribution of biomass in 2010 in Kenyan shrublands and forests from two of the data sources: WCMC and GlobBiomass. Land cover categories are taken from a vector dataset of land cover types that we layered with the biomass raster data (note, the vertical axes differ in magnitude). The distributions show large differences in the same year. 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.

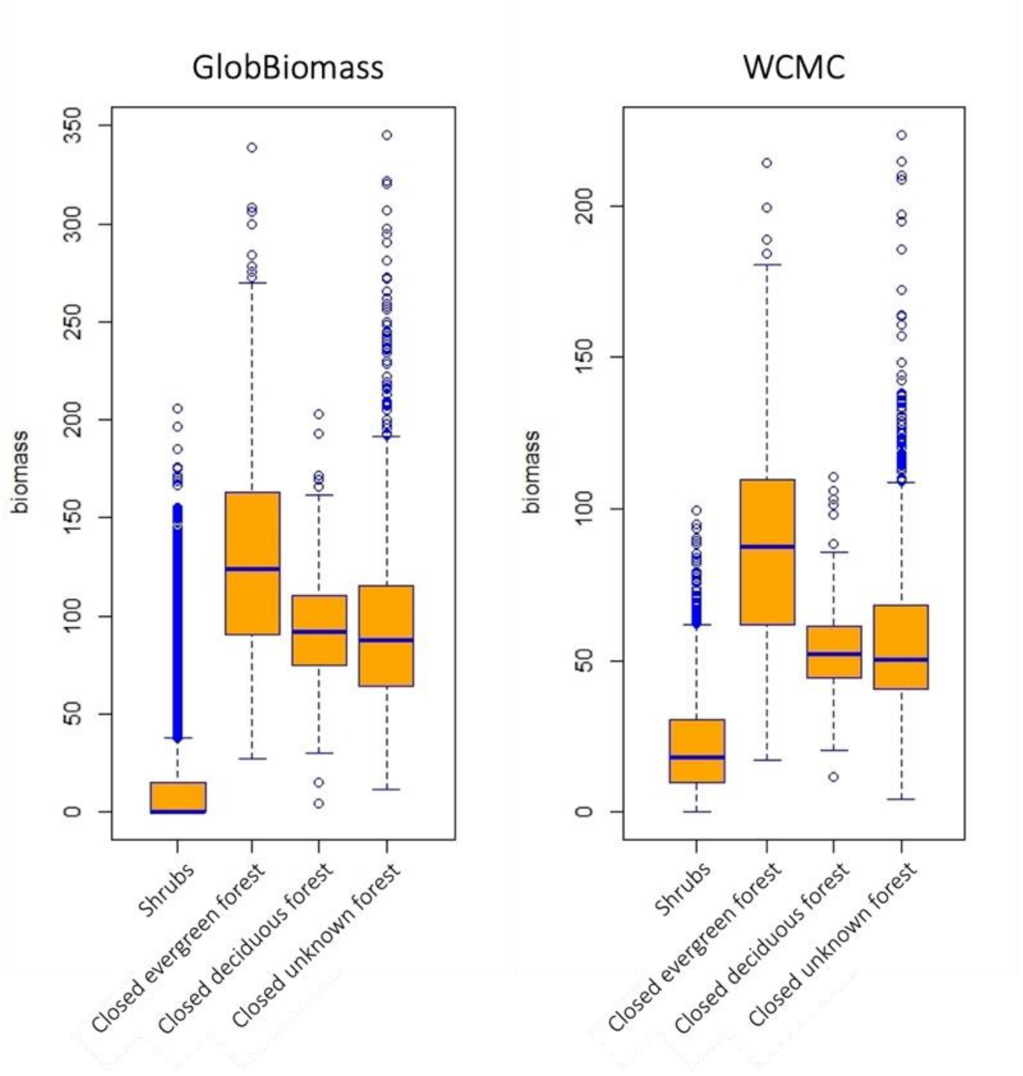
For this assessment we use the WCMC dataset for several reasons:

- the year data is from 2010, which coincides with our base year
- coverage extends beyond tropical regions and includes biomass of non-dominant land cover types within each pixel
- includes pixel-level uncertainty estimates.

In addition, while some concerns about uncertainty introduced by the selection of one biomass stock map over another are warranted, we accommodate this uncertainty explicitly by running Monte Carlo simulations that explicitly account for uncertainty in biomass stocks, a process that we describe in more detail below.

Figure 1: Box-and-whisker plot showing the distribution of above-ground biomass stocks in measured in tons of dry matter per hectare 2010 in common Kenyan land cover types from two global biomass maps (the dark line shows the median of biomass density in each category, 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).



Biomass growth functions

These functions rely on two important parameters: annual growth rate and maximum stock within each pixel.[1] We use the following logistic (sigmoidal) growth function to simulate woody biomass growth in each pixel and land-cover type:

---

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

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

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 biomass in pixel *i* and land cover *j* at time t or t+1
- $r_{max,j}$ is the maximum growth rate in land-cover type *j* (the slope at the inflection point of the sigmoidal growth function)
- K_j is the maximum woody biomass in land-cover type *j* (or "carrying capacity")

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 [11]. The IPCC guidelines provide region-specific woody biomass growth rates for different global ecological zones (GEZ) [12] and land-use land cover (LULC) categories [13]. 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 use the values that represent "< 20 years after disturbance or establishment", which are the highest growth rates reported by the IPCC and are therefore the most appropriate values to simulate the maximum growth rate "r_{max}" in our growth function.

Our maximum biomass stock estimates "K" are derived from the World Conservation Monitoring Centre database described above. Note, in Figure 1, the distribution of woody biomass stocks from this dataset varies widely and includes many outliers. To obtain a reasonable estimate of the maximum potential woody biomass stocks in each region/GEZ/LULC category while avoiding outliers, we mapped the WCMC 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.

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.

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 and reduce tree growth even in the absence of woodfuel demand. In that case, those regions will never reach K_j. Therefore our simulations would be overestimating regrowth and underestimating fNRB.

Table 1: Values of K and rmax and associated standard deviations (SD) used in the global model

GEZ classification	LULC category	Area (km^2)	r_{max} (Mg ha^{-1} yr^{-1})	r_{max}-SD (Mg ha^{-1} yr^{-1})	K (Mg ha^{-1})	K-SD (Mg ha^{-1})
Tropical rainforest	Savannas	1,043,497	7.6	5.9	38	30
Tropical rainforest	Woody Savannas	591,955	7.6	5.9	100	78
Tropical rainforest	Evergreen Broadleaf Forests	1,926,509	7.6	5.9	140	109
Tropical moist forest	Grasslands	1,172,275	2.9	1	26	9
Tropical moist forest	Savannas	1,865,505	2.9	1	34	12
Tropical moist forest	Woody Savannas	506,187	2.9	1	68	23
Tropical dry forest	Grasslands	2,045,193	3.9	3.51	25	23
Tropical dry forest	Savannas	706,186	3.9	3.51	35	31
Tropical shrubland	Barren	1,111,350	0.9	0.81	2	2
Tropical shrubland	Grasslands	2,569,694	0.9	0.81	26	24
Tropical shrubland	Open Shrublands	872,855	0.9	0.81	15	13
Tropical desert	Barren	2,802,496	0.6	0.9	1	2
Tropical desert	Open Shrublands	597,406	0.6	0.9	16	24
Tropical mountain system	Grasslands	522,497	5.5	6.8	30	38

Accounting for other carbon pools

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, particulary 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.

SOC

MoFuSS cannot accommodate SOC. While there are global maps of SOC, these are snapshots and do not demonstrate changes over time [14]. 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.

DOM

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:

1. 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" [15 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).
2. Including deadwood as a distinct source of supply would be very difficult without extensive data collection that is beyond the scope of this assignment. 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 [16].
3. Despite these challenges, 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 was not utilized for this assessment, because the option does not work well for multi-country models.

Biomass consumption

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.[2] 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.

Residential and other sectors

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. We do not include these sources of demand for three reasons. First, there is no reliable data that would allow us to map demand in the same way that we map residential demand (described below). Second, the estimates of industrial wood demand that do exist [17], indicate that in most countries in sub-Saharan Africa, industrial roundwood accounts for less than 10% of the overall wood harvest.[3] Third, much of the supply of industrial wood originates from plantations, which are typically 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.

This raises questions about how MoFuSS should treat 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 in sub-Saharan Africa. There is a recent database of tree plantations, but it has very limited coverage in sub-Saharan Africa [18]. Therefore, the regional MoFuSS model for sub-Saharan Africa 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 [18].

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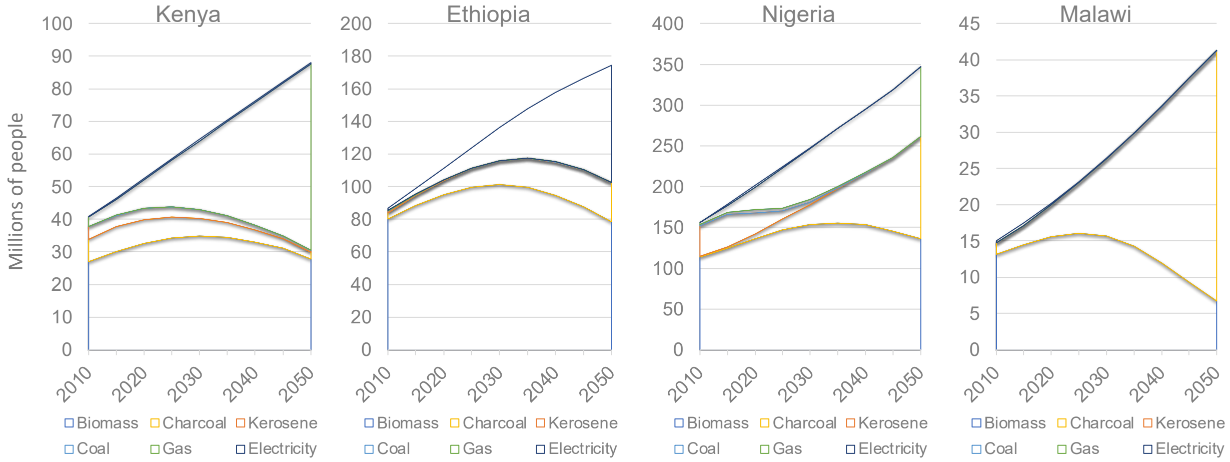
[2] MoFuSS can accommodate more complex demand scenarios that account for secondary and tertiary users. However, stove and fuel stacking data are only available for a small number of countries. Therefore, for this assessment, we only account for primary use.

[3] We arrive at this by comparing FAO's estimates of industrial roundwood production to our estimates of residential fuelwood and charcoal consumption.

Figure 2: Estimated population of primary cooking fuel users for a selection of African countries from WHO's Global HH Energy Model (2010-2050) [19,20]



Quantifying consumption

We have several options to estimate the quantity of each fuel consumed.

1. One option relies on wood consumption data from project design documents (PDDs) submitted to UNFCCC for carbon offset projects. The mean annual per capita wood consumption from 109 CDM PDDs, prior to the introduction of improved stoves or fuel-switching, was 0.74 ± 0.39 tons with some regional variation (Table 2).

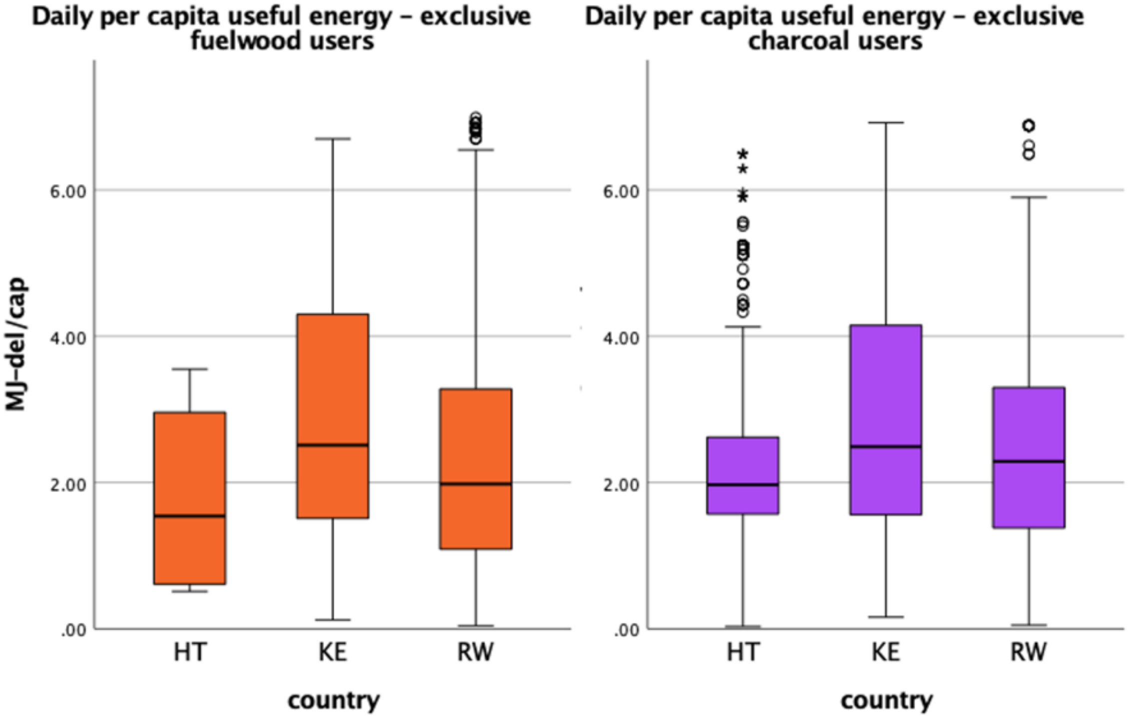
Table 2: Average annual consumption of woody biomass per person

	UN and DHS		PDD values	
Region	No.	tpc/yr	No.	tpc/yr
SSA	33	0.59	58	0.87
W Asia & N Africa	1	0.59	0	-
LAC	8	1.10	6	1.11
E Asia & Pacific	7	0.44	10	0.95
South Asia	5	0.57	35	0.40
Eur & Cent Asia	4	0.32	0	-
Total	58	0.62	109	0.74

2. A second option relies on data compiled from nationally representative household surveys conducted in Rwanda, Kenya, and Haiti which include estimates of annual cooking fuel consumption. Figure 3 shows the distribution of daily per capita cooking energy consumption expressed as units of "energy delivered" from three such surveys for exclusive

users of fuelwood (left) and charcoal (right). Median values from all datasets fall roughly around 2 MJ per person per day, which, converted to annual consumption, becomes ~0.30 tons of wood and ~0.11 tons of charcoal.[4]

Figure 3: Daily cooking energy per capita in units of "energy delivered" for exclusive users of fuelwood (left) and charcoal (right) in Haiti, Kenya, and Rwanda [21–23]



3. A third option is to use the default value currently recommended by the UNFCCC for woodfuel projects, which is 0.4 tons of wood per capita, held constant throughout the entire simulation. We selected this option since it falls between the two previous options.

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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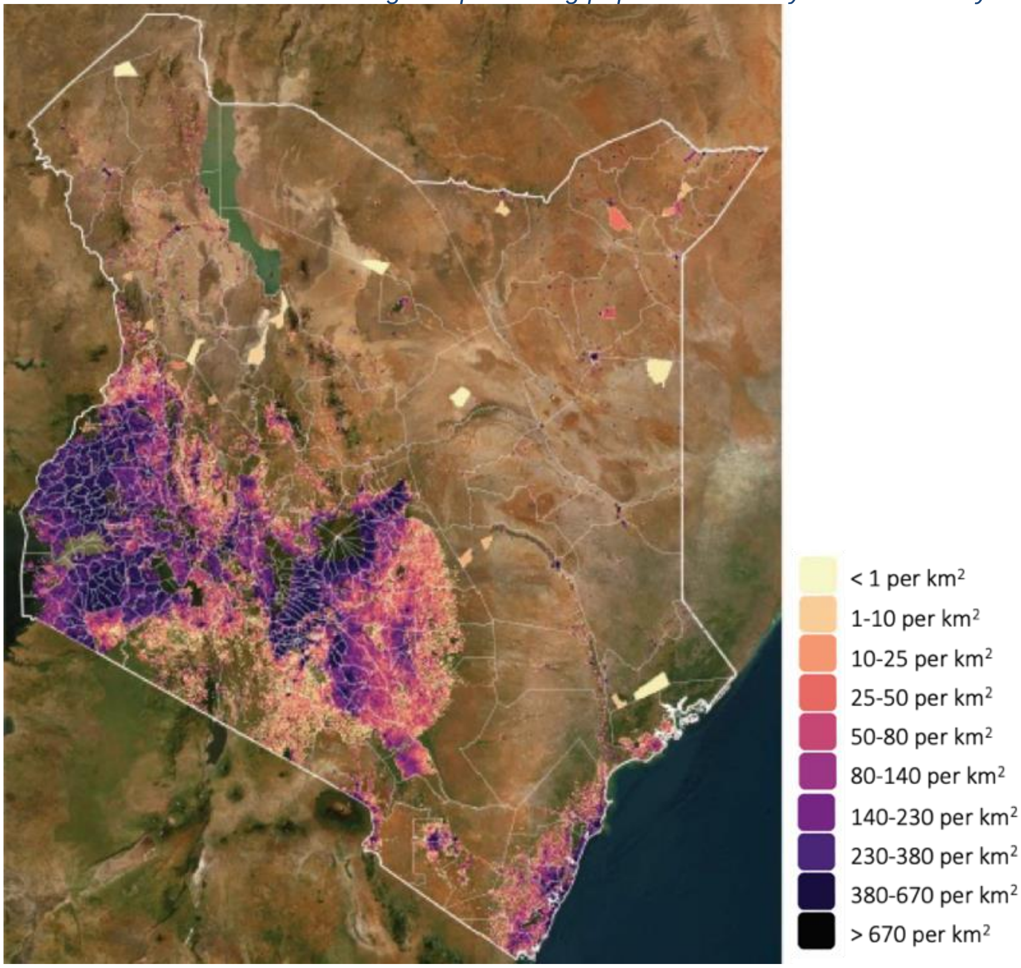
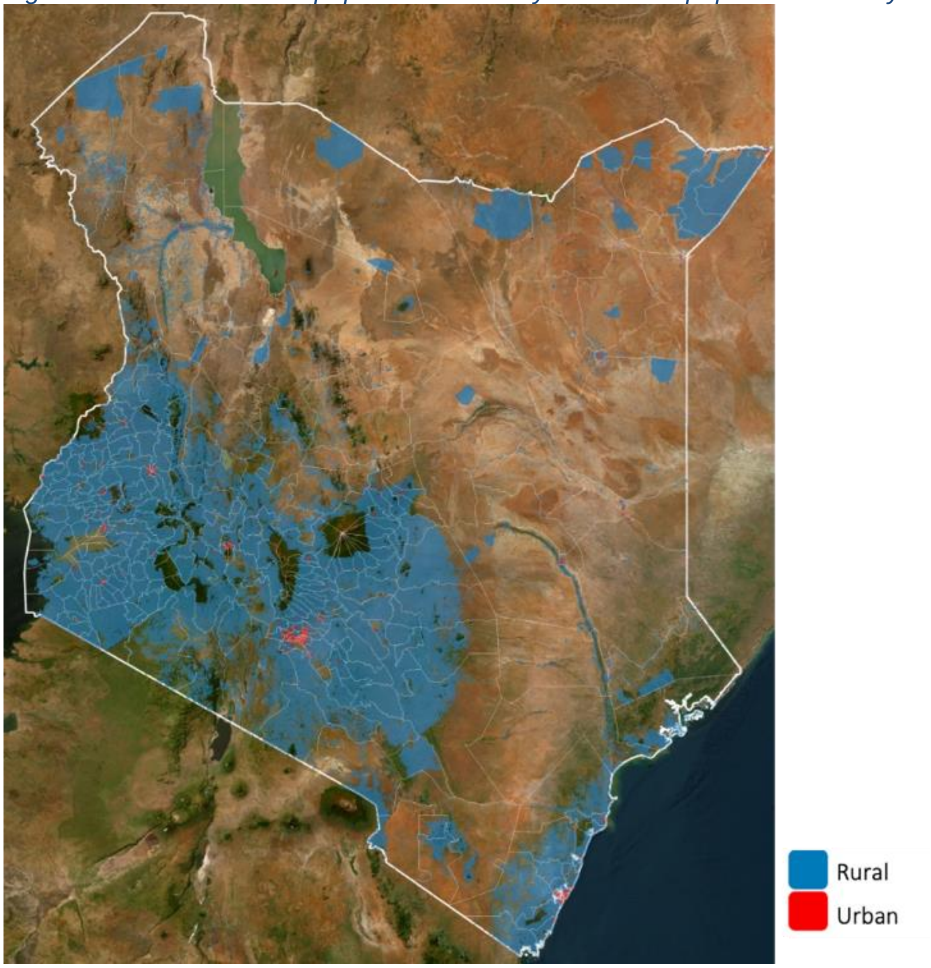
[4] These conversions assume wood stoves are 15% efficient and air-dry wood has a calorific value of 16 MJ/kg and charcoal stoves are 25% efficient and charcoal has a calorific value of 27 MJ/kg.

Figure 4: Humanitarian Data Exchange map showing population density deciles in Kenya



1. **Obtain spatial population distribution data.** For this, we use population density maps published by Humanitarian Data Exchange (HDX), which has recent, freely available, high-resolution data for most countries included in this study. Figure 4 shows an example of HDX data from Kenya.

Figure 5: Rural and urban populations in Kenya based on population density from HDX data

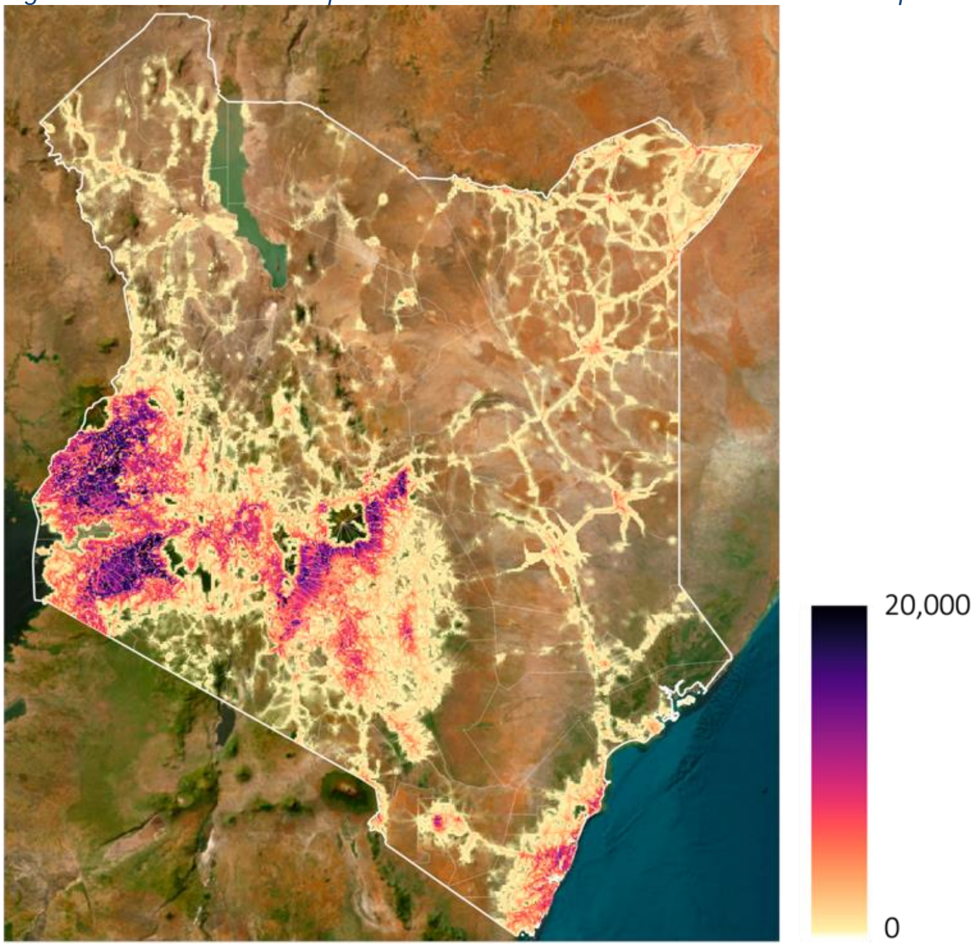


2. **Map fuel use among the population.** For this, we use the WHO's fuel use projections, which are disaggregated by urban and rural populations. However, HDX data doesn't differentiate between urban and rural areas. To make this distinction, we define urban and rural areas by ranking all pixels from the HDX 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 [24]. The pixels that add to the urban cut-off are defined as urban and the remaining pixels are defined as rural. Figure 5 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 thus 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 [24].[5]

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 6 shows a map of cumulative woodfuel consumption between 2010 and 2050 for Kenya.

Figure 6: Woodfuel consumption between 2010 and 2050 measured in tons per km²



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[5] This assumption is not necessarily accurate but it is beyond the scope of this model to predict how urban areas might grow over a 20 or 30 year period.

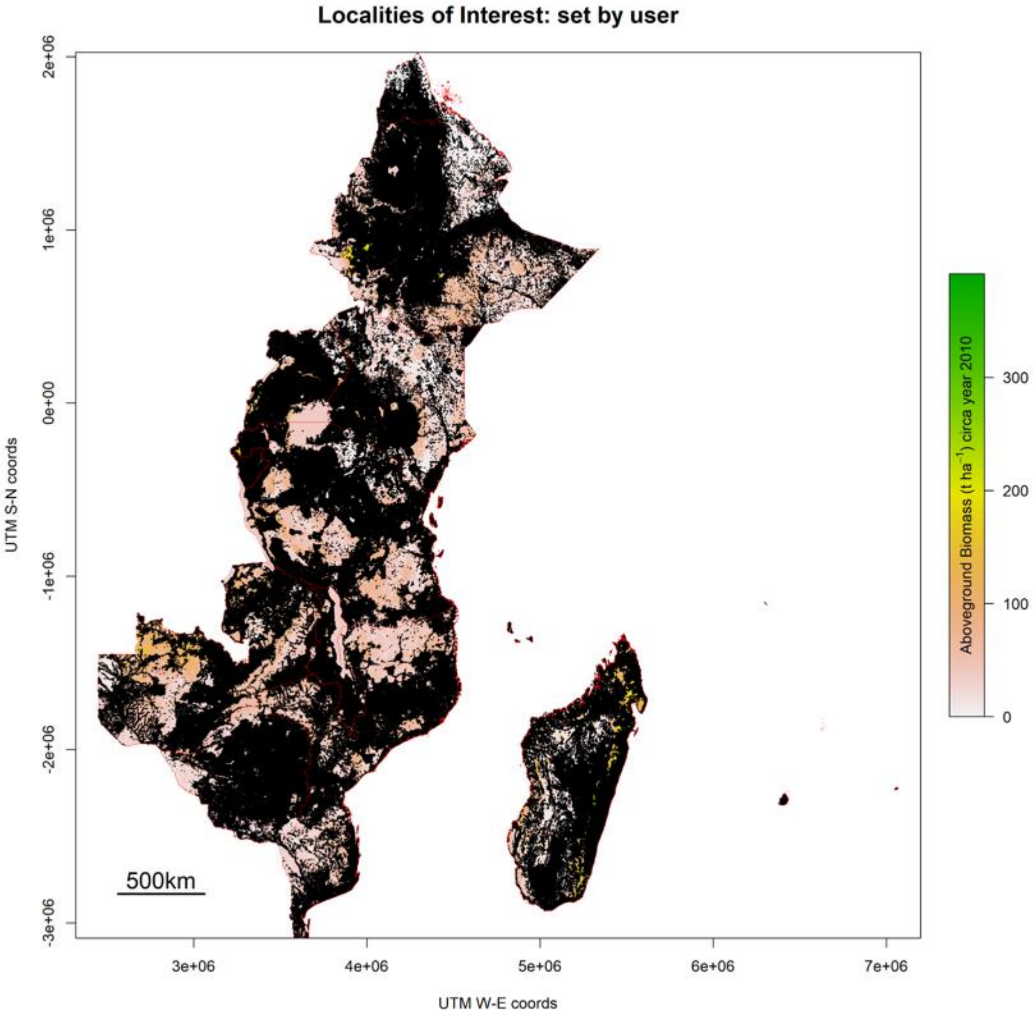
Spatializing biomass harvesting

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:

1. **Pressure maps**
   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 ~3.3 million populated pixels spread throughout sub-Saharan Africa (Figure 7). Using MoFuSS, we calculated pressure maps for each of these populated points, which allowed us to create maps of biomass harvesting over the continent.

2. **Annual reassessments**
   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 [19]), which result in changes in demand for both collected and marketed woodfuels. To accommodate these changes, we generated 267 million accessibility maps needed to account for changing population distribution using self-collected and commercial woodfuels across SSA between 2010 and 2050. This was accomplished by developing novel code in C++ and using high-performance computing. Figure 8 shows the combined pressure maps for commercial woodfuels in 2010, the first year of our simulation.

Figure 7: Populated places in East Africa accounting for some amount of woodfuel consumption as fuelwood or charcoal[6]



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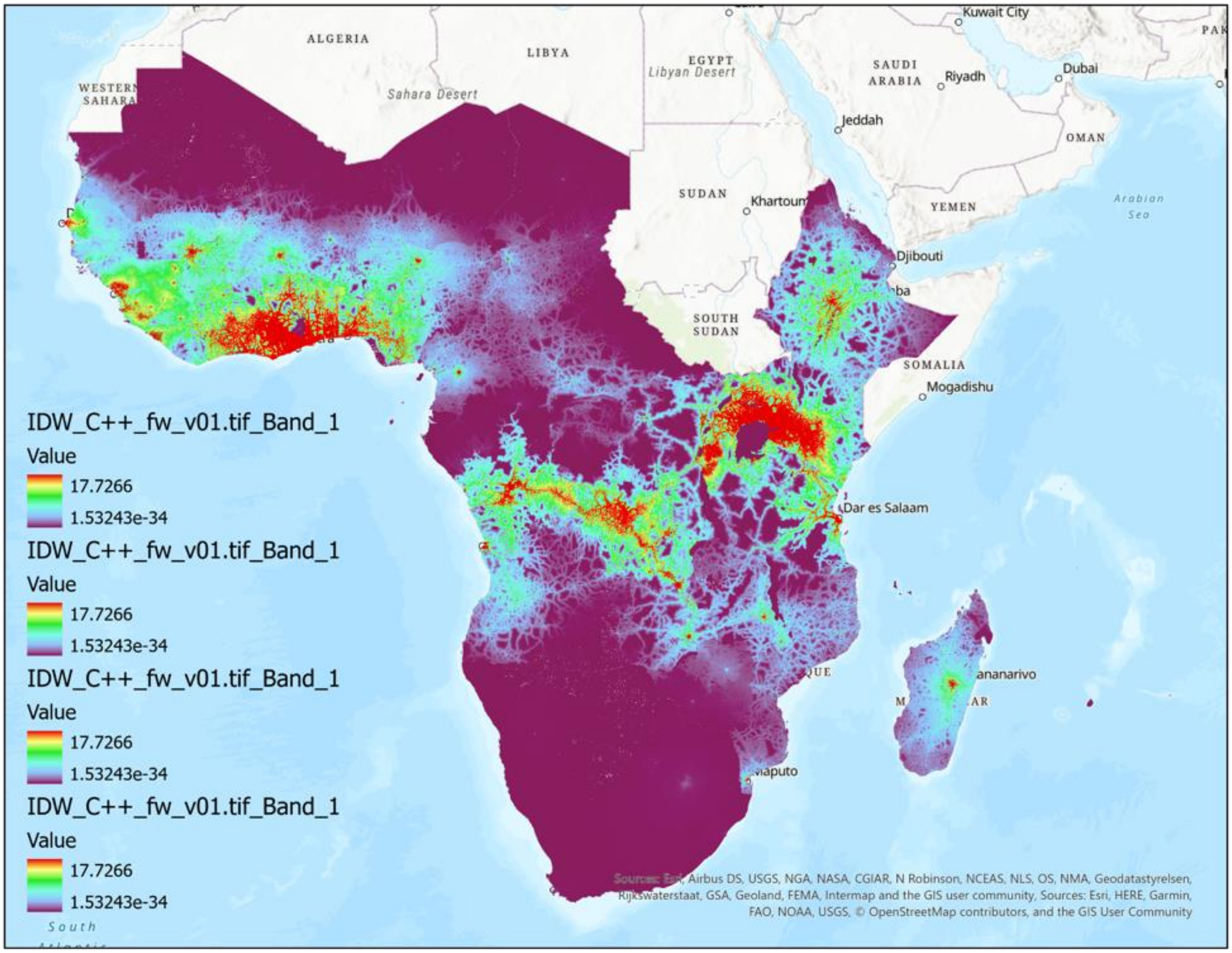
[6] Each black dot represents a populated pixel. A key innovation in this version of MoFuSS is that it respects the actual distribution of people using fuelwood and projects the harvesting pressure proportionally to the amount of fuelwood and charcoal within that 1 km x 1 km area.

Figure 8: Pressure map to seed biomass harvesting places for commercial woodfuels for the year 2010.



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

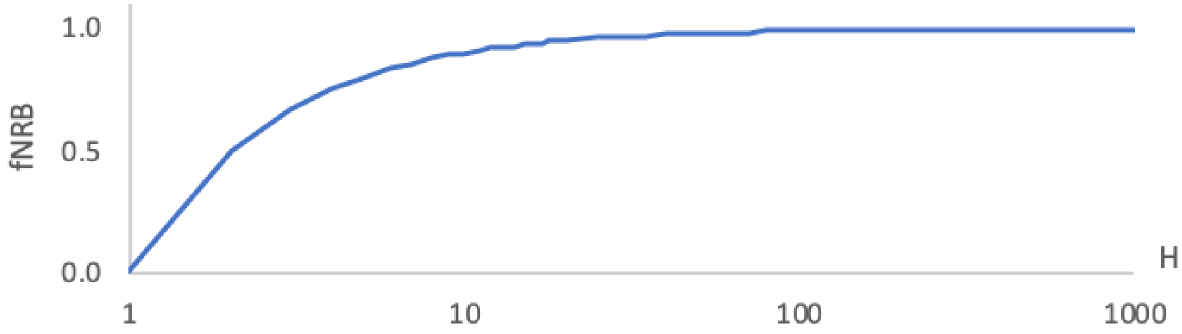
The relationship between consumption and fNRB

Under the TOOL30 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:

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

This results in a relationship like the plot in Figure 9 (note the x-axis is logarithmic).

Figure 9: fNRB as a function of H (expressed as a %of MAI)



However, in reality MAI is not a constant. Rather it varies over time and is affected by harvesting. MAI is also sensitive to the time-horizon of the analysis. MoFuSS avoids using MAI and uses growth curves as explained above. However, this makes it difficult to predict how the model responds to different choices of H because the response depends on the growth function parameters discussed in the previous sections.

Calculating fNRB

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. This approach generally results in lower fNRB than the approach defined in TOOL30.

In addition, there are other assumptions that also affect fNRB, but the sensitivity of the model is not as large as the variables described above. Please refer to the supplementary material of Ghilardi et al 2016 [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. Below, we summarize some of this trying to be as concise as possible.

Biomass harvest and NRB in MoFuSS

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.

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 in 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.

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.

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

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 entire “woodfuel-shed”. Instead, it accounts for losses of AGB only in the set of pixels where a loss occurred.

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

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:

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

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.

Use of deforestation by-products

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 [25]. 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 [26]. However, in some situations, the by-products of land clearance are used for firewood or charcoal production [27,28]. 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.

Treatment of Protected Areas

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.

National boundaries and trade

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.

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 [17] includes woodfuel imports and exports, but the accuracy of this data is unclear and there is no information about trading partners

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.[7] Within regions, crossing borders adds “friction” or travel time for wood suppliers, making it more costly, but not impossible, for them to access wood in neighboring countries.

Prune factor

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 (i.e. one year in our global model), and how much wood should 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

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

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.

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 30m resolution, it is unrealistic for every pixel to be visited every year and we would adjust the prune rate to something less than 100%.

Results

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

First, MoFuSS produces a variety of results in various formats. The essential GIS-based results for Sub-Saharan Africa (SSA) will be available in the long run in this Google Drive folder. 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*.

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

Third, MoFuSS is a spatial analysis and modeling tool. After setting the input parameters, it can be run from cradle to grave with very little intervention.[8] At the moment of writing this report, we are currently running BaU and woodfuel savings scenarios for 2010-2050, with 30 Monte Carlos MoFuSS for the entire Sub-Saharan African region. We expect these analyses to be completed by 10 Oct. All these results will be uploaded automatically to the same Google Drive folder shared above, and can be reviewed by the Meth Panel any time after that date.[9]

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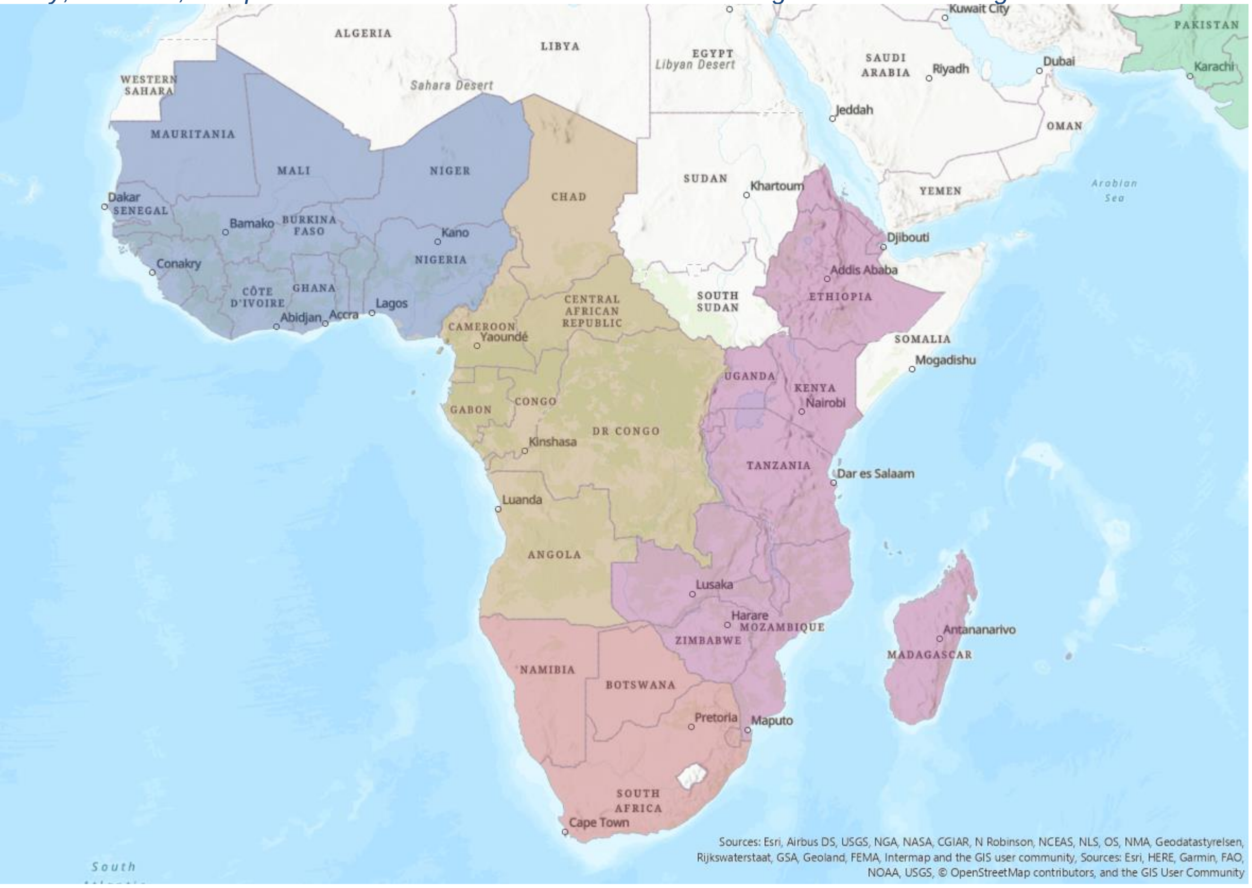
[8] It is also entirely free and open-source, for the sake of reproducibility of results by anyone interested in doing so, or even going farther and using different datasets and parameters. However, analyzing large areas requires access to high-performance computers.

[9] A new version of MoFuSS to be released by the beginning of 2024 will run each Monte Carlo realization in parallel, speeding the entire process by a factor of up to 100x.

Finally, as shown in Figure 10. SSA Africa was divided in four regions, originally to save processing time, as running the entire continent could have taken too long during the development process.

Figure 10: MoFuSS was split into four subregions to save processing time during the development of this study; however, an updated model of the continent without sub-regions is forthcoming



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

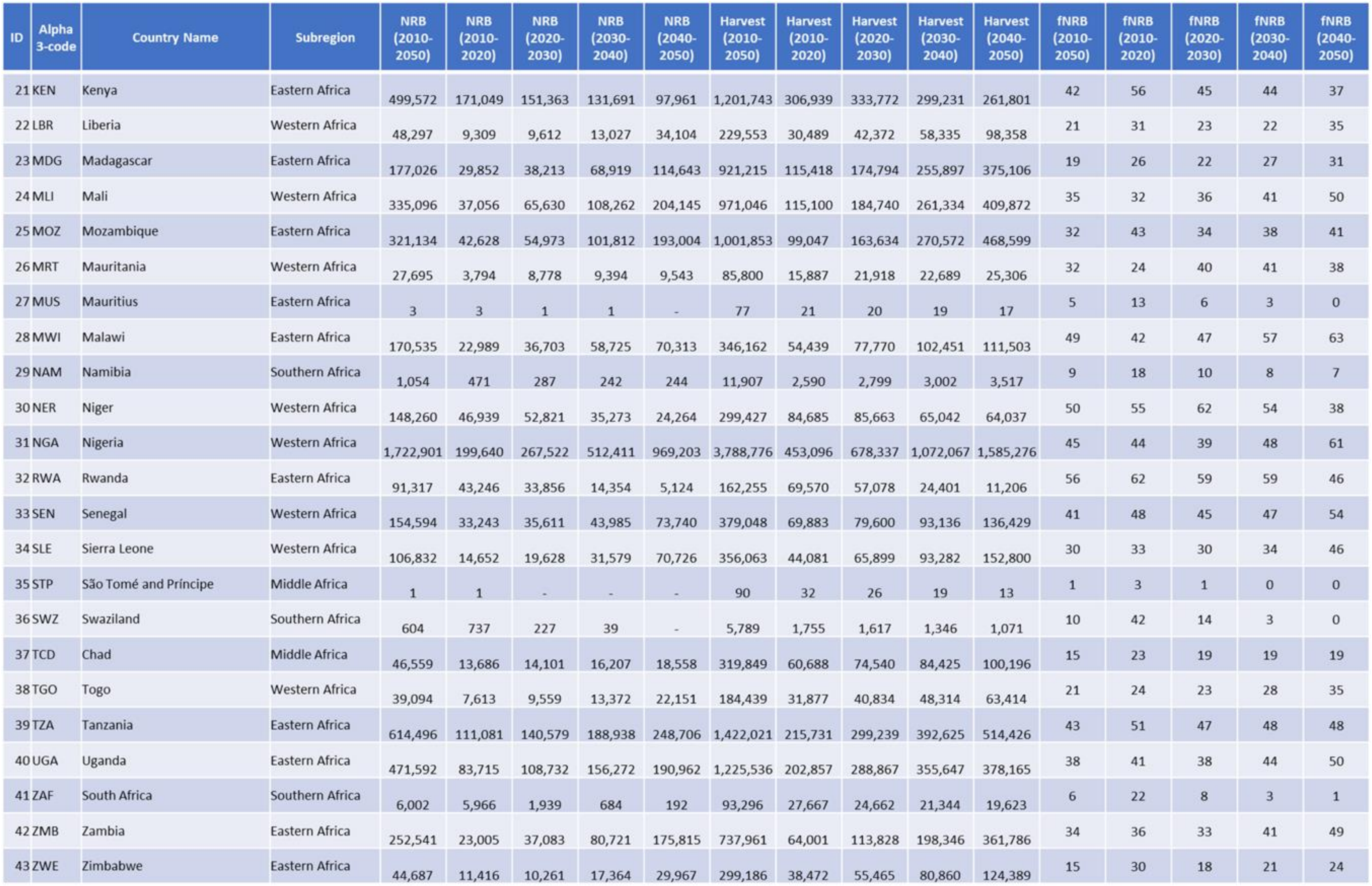
Updated fNRB values for sub-Saharan African countries

In this first phase, we ran MoFuSS for 43 countries in Sub-Saharan Africa (SSA). The selection was made based on the availability and coverage of harmonised input datasets such as population, primary cooking fuel, aboveground biomass, land use cover, among others (explained above). Table 3 shows a summary of national woodfuel sustainability variables SSA, with NRB and fNRB calculated as described in Equations 3-5. Figure 11 - 13 show regional maps of fNRB for the full simulation (2010-2050) and for projects currently being implemented or planned (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 shared above.

Figure 11 - 13 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 and woody biomass consumption. Those results are shown for the full region in Figure 14 and 15 below.

Table 3: NRB and fNRB at the country level for SSA countries (part I)

ID	Alpha 3-code	Country Name	Subregion	NRB (2010-2050)	NRB (2010-2020)	NRB (2020-2030)	NRB (2030-2040)	NRB (2040-2050)	Harvest (2010-2050)	Harvest (2010-2020)	Harvest (2020-2030)	Harvest (2030-2040)	Harvest (2040-2050)	fNRB (2010-2050)	fNRB (2010-2020)	fNRB (2020-2030)	fNRB (2030-2040)	fNRB (2040-2050)
1	AGO	Angola	Middle Africa	112,761	46,366	33,702	29,433	31,923	568,691	110,420	131,867	147,412	178,993	20	42	26	20	18
2	BDI	Burundi	Eastern Africa	89,236	35,973	36,862	16,725	5,264	157,704	60,402	61,111	26,433	9,757	57	60	60	63	54
3	BEN	Benin	Western Africa	141,858	20,304	26,208	41,966	74,720	371,246	52,260	75,389	102,846	140,751	38	39	35	41	53
4	BFA	Burkina Faso	Western Africa	130,541	22,870	31,502	46,022	74,819	546,604	86,181	116,872	144,833	198,719	24	27	27	32	38
5	BWA	Botswana	Southern Africa	660	345	198	138	103	9,368	2,232	2,316	2,328	2,493	7	15	9	6	4
6	CAF	Central African Republic	Middle Africa	51,516	12,271	11,278	14,633	20,469	157,630	22,041	29,685	42,232	63,673	33	56	38	35	32
7	CIV	Côte d'Ivoire	Western Africa	103,635	45,503	25,029	22,808	42,806	586,238	119,378	130,474	140,921	195,465	18	38	19	16	22
8	CMR	Cameroon	Middle Africa	143,796	34,537	36,066	45,669	52,479	489,803	71,990	100,829	136,154	180,831	29	48	36	34	29
9	COD	Democratic Republic of the Congo	Middle Africa	978,010	187,597	223,304	324,515	483,707	3,547,134	465,830	694,673	973,282	1,413,349	28	40	32	33	34
10	COG	Republic of the Congo	Middle Africa	51,320	13,363	12,392	16,658	25,145	237,734	34,085	46,613	63,173	93,863	22	39	27	26	27
11	COM	Comoros	Eastern Africa	116	34	30	35	39	864	145	183	235	302	13	24	16	15	13
12	DJI	Djibouti	Eastern Africa	3,579	667	871	1,027	1,176	6,509	1,004	1,420	1,805	2,281	55	66	61	57	52
13	ERI	Eritrea	Eastern Africa	22,614	4,870	5,280	7,561	10,013	86,279	13,181	17,711	23,566	31,822	26	37	30	32	31
14	ETH	Ethiopia	Eastern Africa	764,209	170,812	193,578	250,614	293,488	2,412,431	389,166	537,661	674,067	811,537	32	44	36	37	36
15	GAB	Gabon	Middle Africa	3,887	1,443	1,047	963	1,061	10,765	2,202	2,418	2,762	3,383	36	66	43	35	31
16	GHA	Ghana	Western Africa	142,060	36,877	32,966	42,558	81,902	747,726	132,676	161,532	189,908	263,609	19	28	20	22	31
17	GIN	Guinea	Western Africa	335,263	59,634	67,842	91,426	157,547	858,552	106,883	161,787	230,066	359,816	39	56	42	40	44
18	GMB	Gambia	Western Africa	15,341	1,545	2,523	4,766	9,185	40,920	4,982	7,811	11,424	16,704	37	31	32	42	55
19	GNB	Guinea-Bissau	Western Africa	29,175	5,875	5,942	7,634	13,465	76,373	9,719	14,138	19,932	32,584	38	60	42	38	41
20	GNQ	Equatorial Guinea	Middle Africa	5,243	1,158	1,309	1,557	1,673	11,993	1,584	2,404	3,401	4,603	44	73	54	46	36



ID	Alpha 3-code	Country Name	Subregion	NRB (2010-2050)	NRB (2010-2020)	NRB (2020-2030)	NRB (2030-2040)	NRB (2040-2050)	Harvest (2010-2050)	Harvest (2010-2020)	Harvest (2020-2030)	Harvest (2030-2040)	Harvest (2040-2050)	fNRB (2010-2050)	fNRB (2010-2020)	fNRB (2020-2030)	fNRB (2030-2040)	fNRB (2040-2050)
21	KEN	Kenya	Eastern Africa	499,572	171,049	151,363	131,691	97,961	1,201,743	306,939	333,772	299,231	261,801	42	56	45	44	37
22	LBR	Liberia	Western Africa	48,297	9,309	9,612	13,027	34,104	229,553	30,489	42,372	58,335	98,358	21	31	23	22	35
23	MDG	Madagascar	Eastern Africa	177,026	29,852	38,213	68,919	114,643	921,215	115,418	174,794	255,897	375,106	19	26	22	27	31
24	MLI	Mali	Western Africa	335,096	37,056	65,630	108,262	204,145	971,046	115,100	184,740	261,334	409,872	35	32	36	41	50
25	MOZ	Mozambique	Eastern Africa	321,134	42,628	54,973	101,812	193,004	1,001,853	99,047	163,634	270,572	468,599	32	43	34	38	41
26	MRT	Mauritania	Western Africa	27,695	3,794	8,778	9,394	9,543	85,800	15,887	21,918	22,689	25,306	32	24	40	41	38
27	MUS	Mauritius	Eastern Africa	3	3	1	1	-	77	21	20	19	17	5	13	6	3	0
28	MWI	Malawi	Eastern Africa	170,535	22,989	36,703	58,725	70,313	346,162	54,439	77,770	102,451	111,503	49	42	47	57	63
29	NAM	Namibia	Southern Africa	1,054	471	287	242	244	11,907	2,590	2,799	3,002	3,517	9	18	10	8	7
30	NER	Niger	Western Africa	148,260	46,939	52,821	35,273	24,264	299,427	84,685	85,663	65,042	64,037	50	55	62	54	38
31	NGA	Nigeria	Western Africa	1,722,901	199,640	267,522	512,411	969,203	3,788,776	453,096	678,337	1,072,067	1,585,276	45	44	39	48	61
32	RWA	Rwanda	Eastern Africa	91,317	43,246	33,856	14,354	5,124	162,255	69,570	57,078	24,401	11,206	56	62	59	59	46
33	SEN	Senegal	Western Africa	154,594	33,243	35,611	43,985	73,740	379,048	69,883	79,600	93,136	136,429	41	48	45	47	54
34	SLE	Sierra Leone	Western Africa	106,832	14,652	19,628	31,579	70,726	356,063	44,081	65,899	93,282	152,800	30	33	30	34	46
35	STP	São Tomé and Príncipe	Middle Africa	1	1	-	-	-	90	32	26	19	13	1	3	1	0	0
36	SWZ	Swaziland	Southern Africa	604	737	227	39	-	5,789	1,755	1,617	1,346	1,071	10	42	14	3	0
37	TCD	Chad	Middle Africa	46,559	13,686	14,101	16,207	18,558	319,849	60,688	74,540	84,425	100,196	15	23	19	19	19
38	TGO	Togo	Western Africa	39,094	7,613	9,559	13,372	22,151	184,439	31,877	40,834	48,314	63,414	21	24	23	28	35
39	TZA	Tanzania	Eastern Africa	614,496	111,081	140,579	188,938	248,706	1,422,021	215,731	299,239	392,625	514,426	43	51	47	48	48
40	UGA	Uganda	Eastern Africa	471,592	83,715	108,732	156,272	190,962	1,225,536	202,857	288,867	355,647	378,165	38	41	38	44	50
41	ZAF	South Africa	Southern Africa	6,002	5,966	1,939	684	192	93,296	27,667	24,662	21,344	19,623	6	22	8	3	1
42	ZMB	Zambia	Eastern Africa	252,541	23,005	37,083	80,721	175,815	737,961	64,001	113,828	198,346	361,786	34	36	33	41	49
43	ZWE	Zimbabwe	Eastern Africa	44,687	11,416	10,261	17,364	29,967	299,186	38,472	55,465	80,860	124,389	15	30	18	21	24

Figure 11: National fNRB values averaged over 2010-2050 (top) and 2020-2030 (bottom)

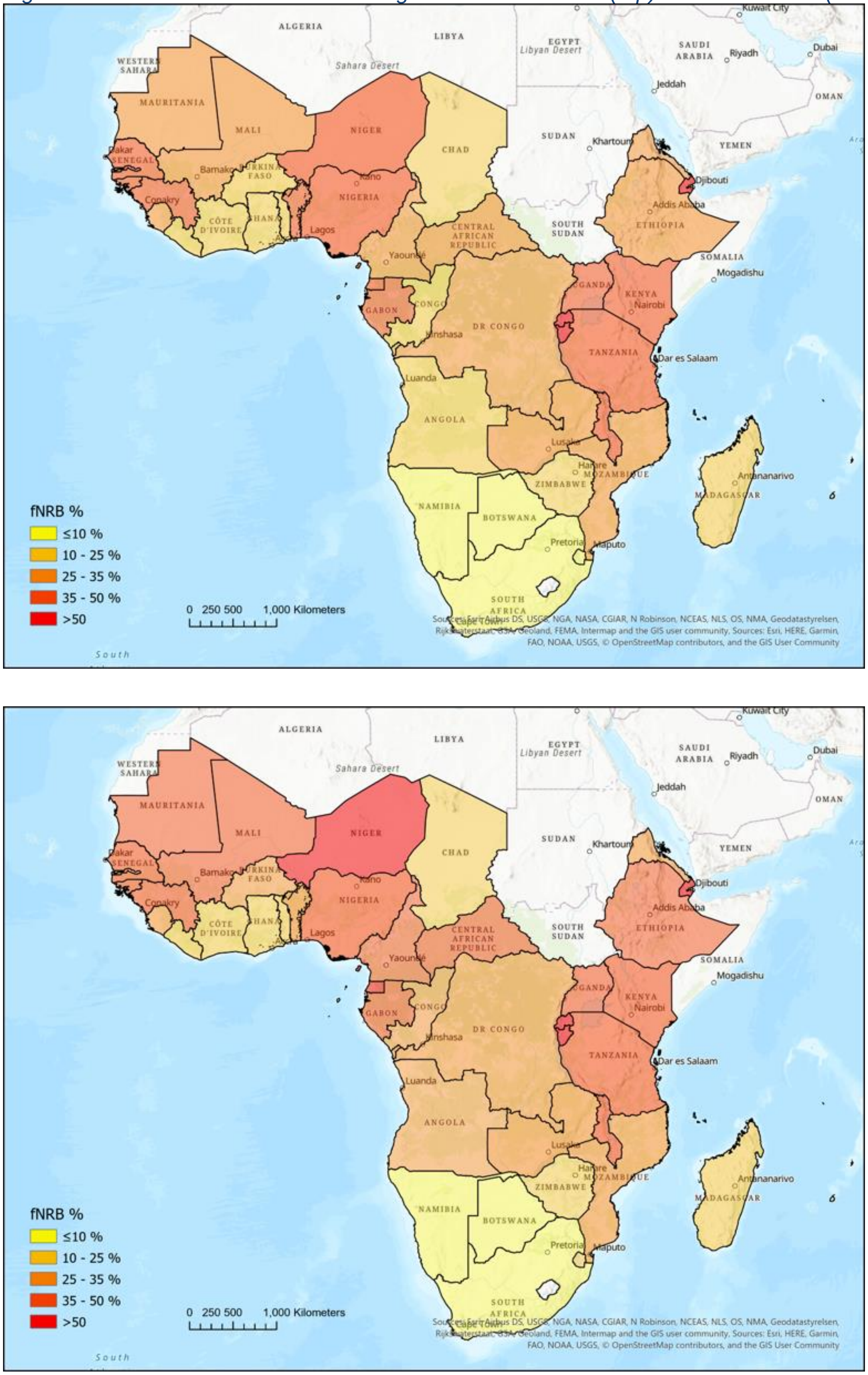
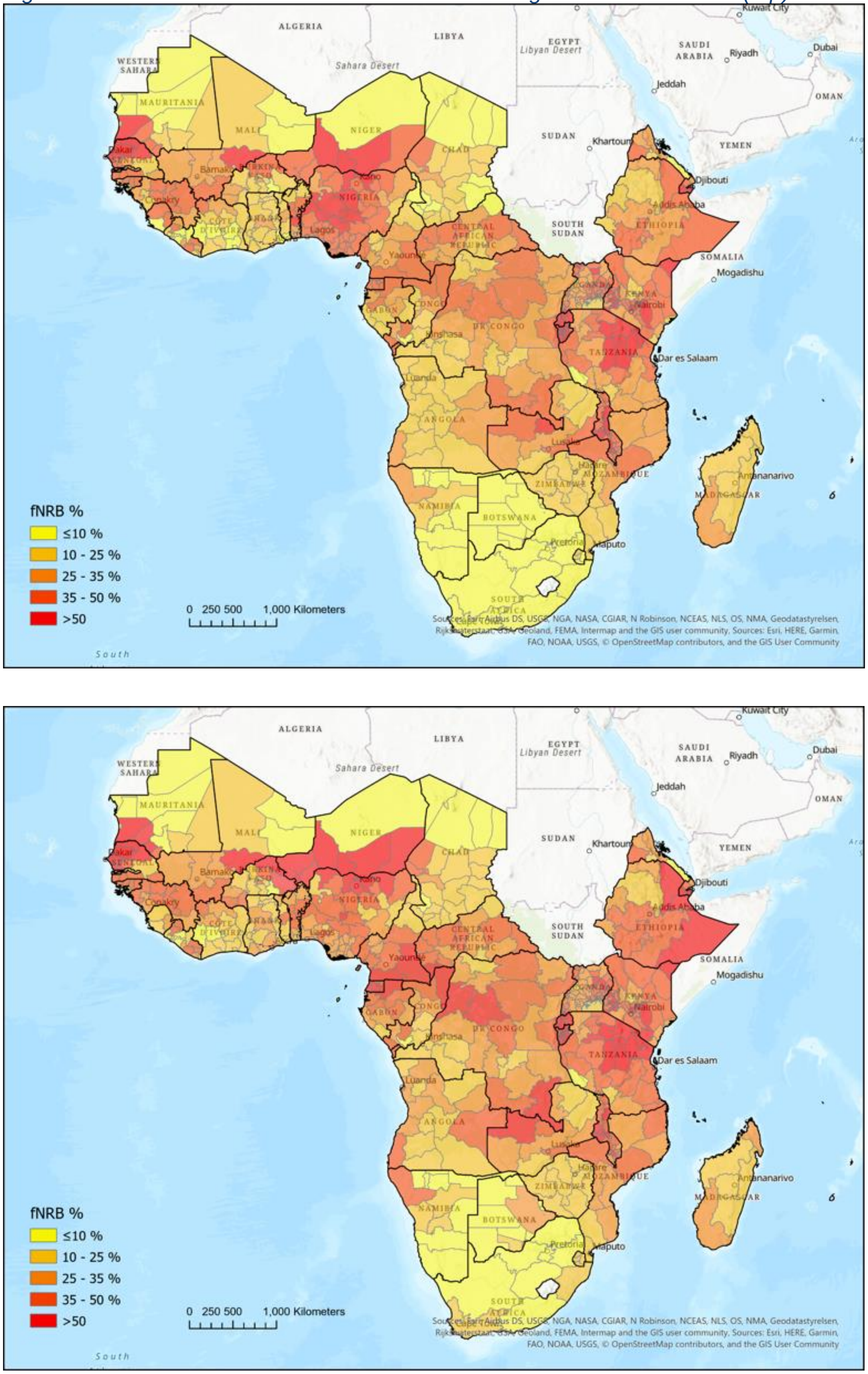


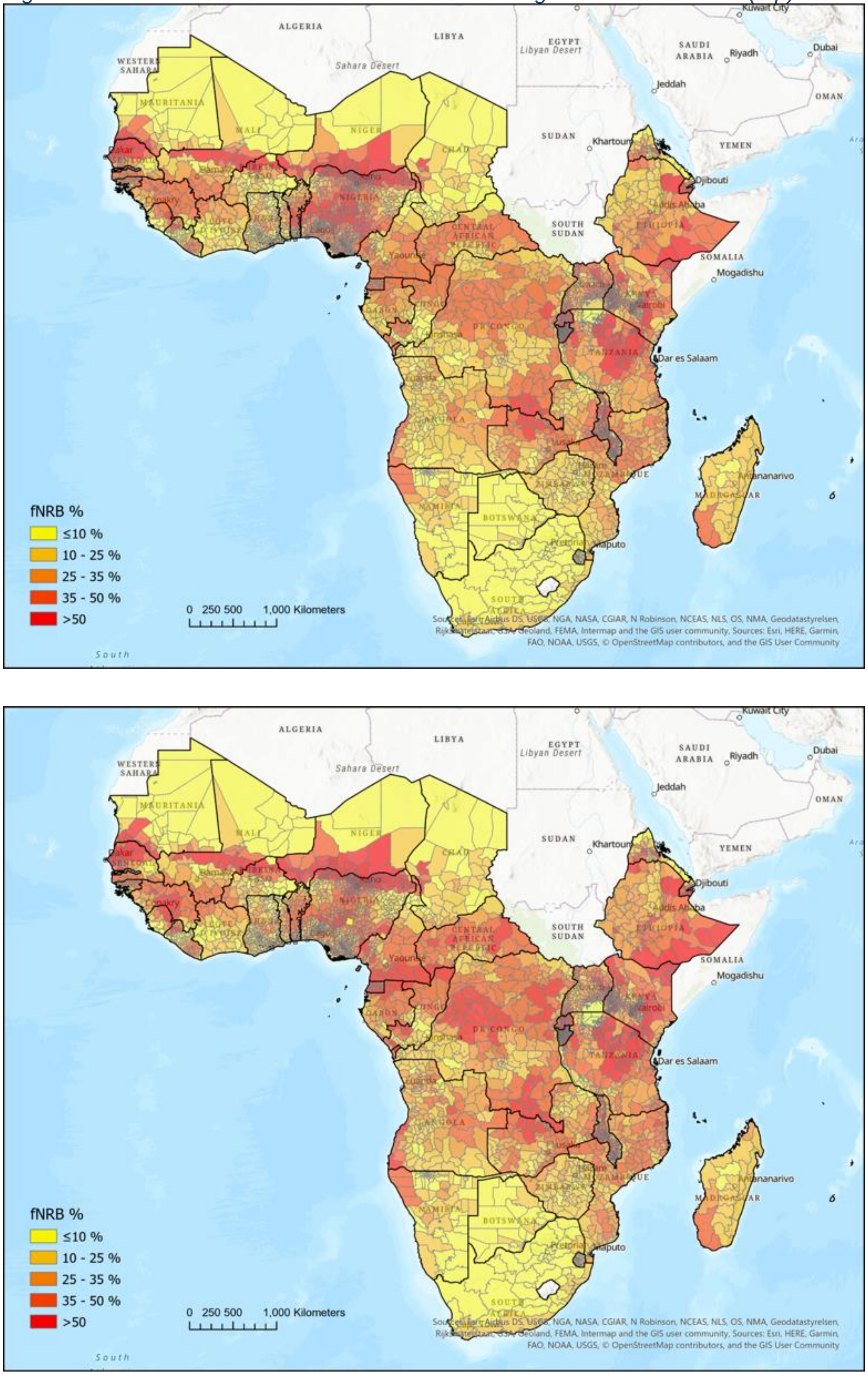
Figure 12: fNRB at the 1st administrative level averaged over 2010-2050 (top) and 2020-2030 (bottom)



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

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

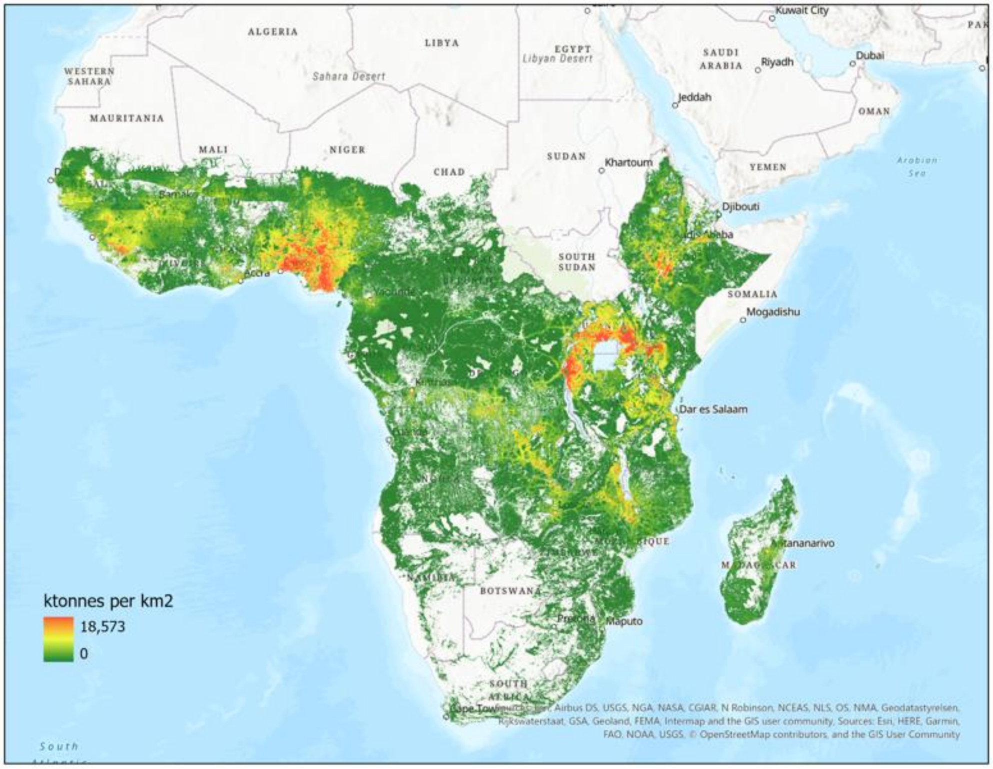
Figure 13: fNRB at the 2nd administrative level averaged over 2010-2050 (top) and 2020-2030 (bottom)



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

By examining the maps in Figure 11 - 13 it is clear that there is spatial variation across regions throughout sub-Saharan Africa. 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 [19]. 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 14: NRB values for the period 2010-2050 *(ktons dry matter per km^2)*



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

It is also instructive to zoom in for a more detailed view of the results. Figure 16 - 18 show unsustainable harvest (NRB), overall harvest, and fNRB in the Gulf of Guinea region of West Africa.

Figure 15: Wood harvest for fuelwood and charcoal for the period 2010-2050 (ktons dry matter per km²)

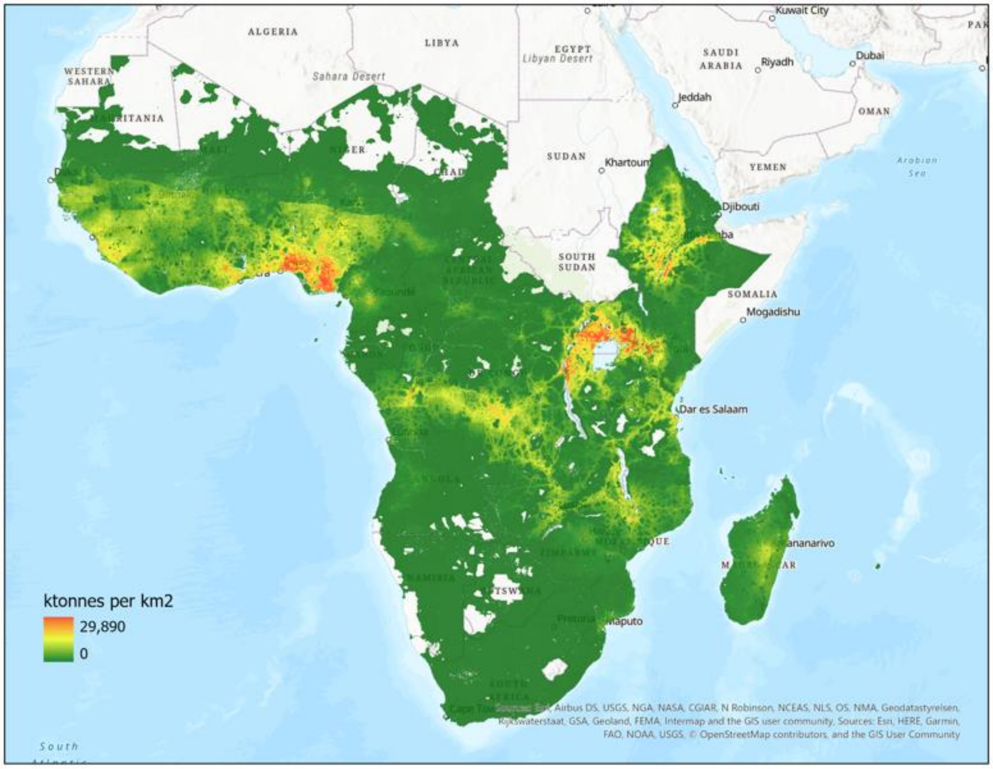


Figure 16: NRB values for the period 2010-2050 - zoom over Gulf of Guinea (ktons dry matter per km²)

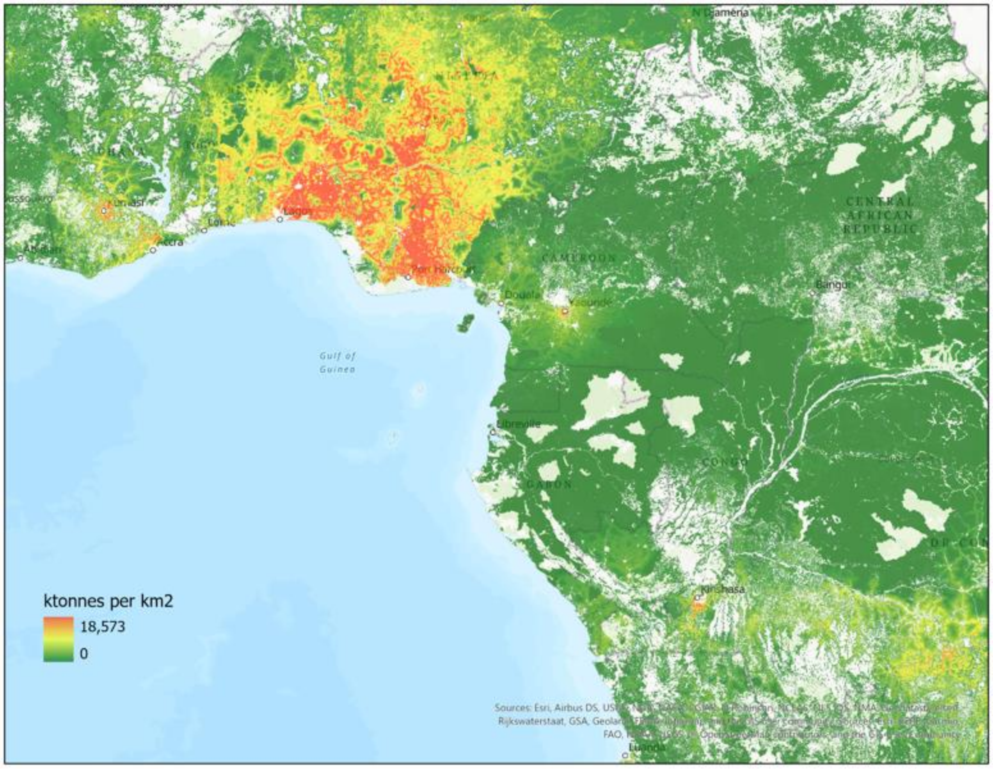


Figure 17: Wood harvest for fuelwood and charcoal for the period 2010-2050 - zoom over Gulf of Guinea (ktons dry matter per km^2)

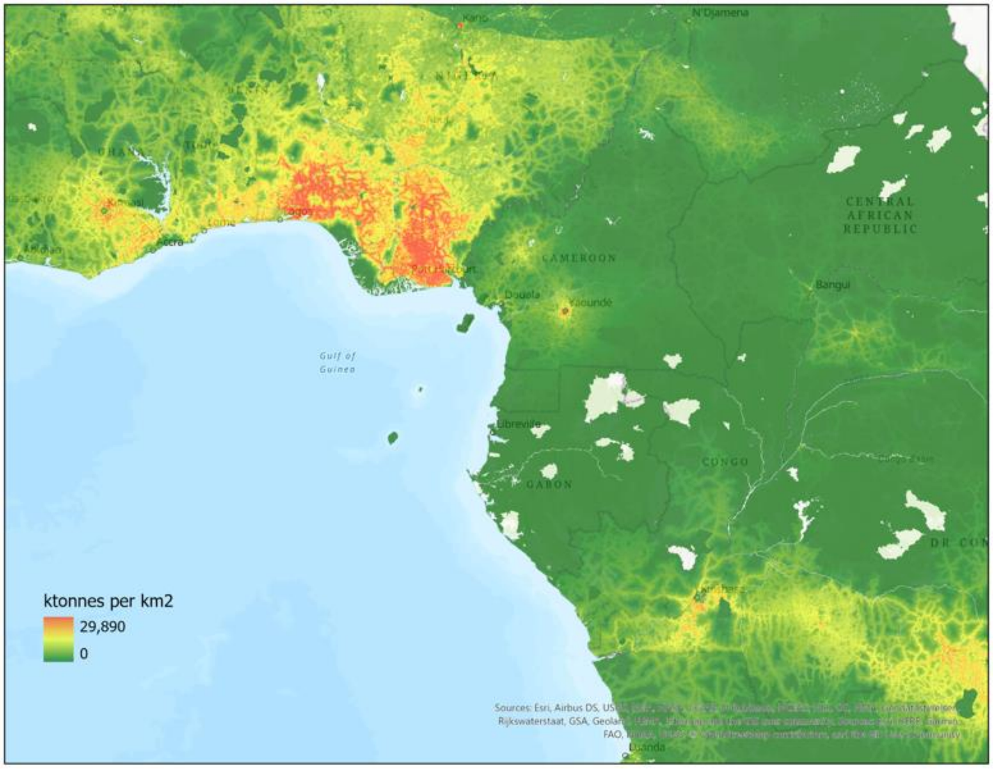
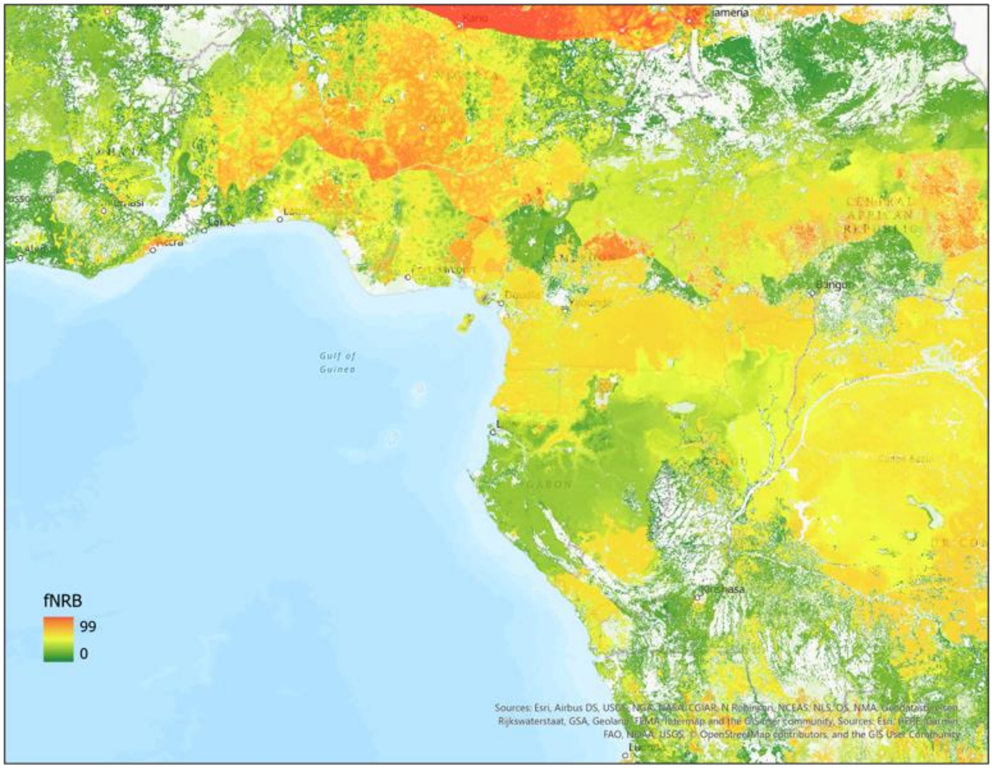


Figure 18: fNRB values in each 1 km^2 pixel for the period 2010-2050 - zoom over Gulf of Guinea



Proposed changes to TOOL30

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 [29]. 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 [30].

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 [16]. 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 [31] to create less ambiguous estimates of growth rates.

How sensitive are MoFuSS fNRB results to input parameters?

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 19), selected to enable quick processing of multiple Monte-Carlo runs.

We ran MoFuSS over the Area of Interest through five simulations, each using 30 Monte Carlo realizations. We sued the same global datasets as for the full regional assessment, but varied the parameters listed in Table 4 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 19: Case study to test for the sensitivity of woodfuel sustainability to input parameters variations

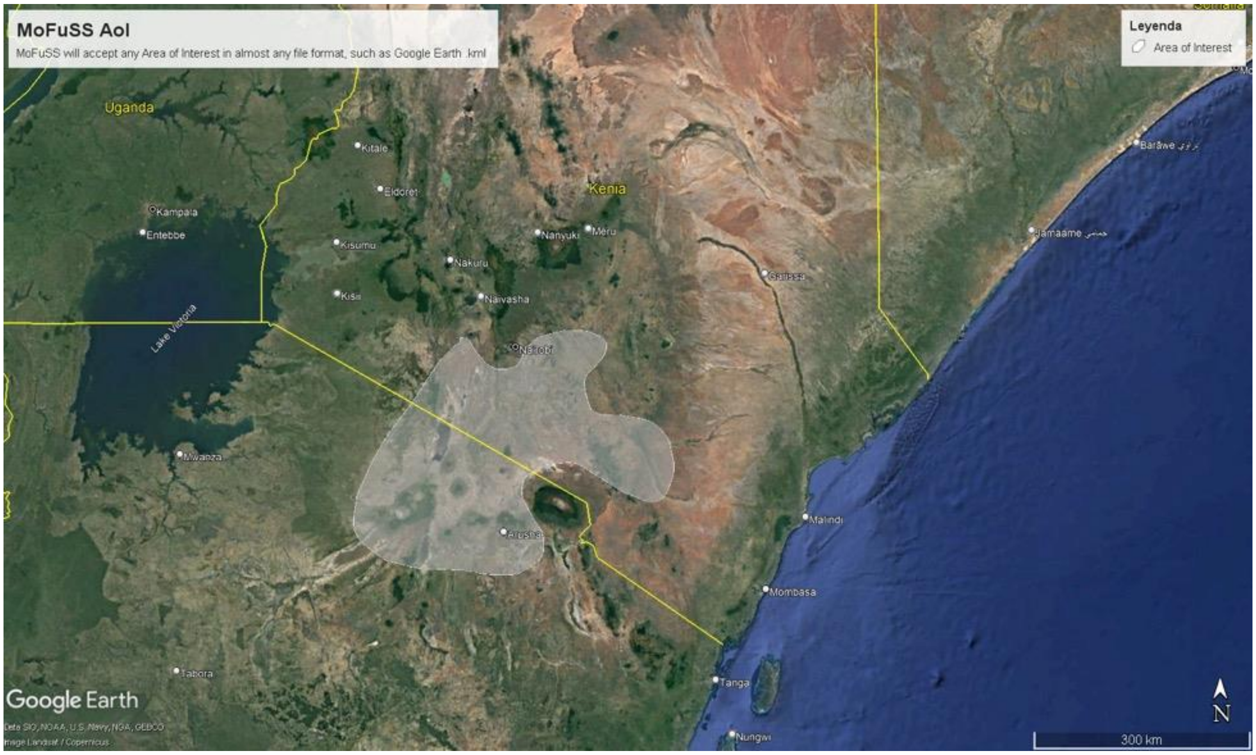


Table 4: Uncertainty and sensitivities in MoFuSS

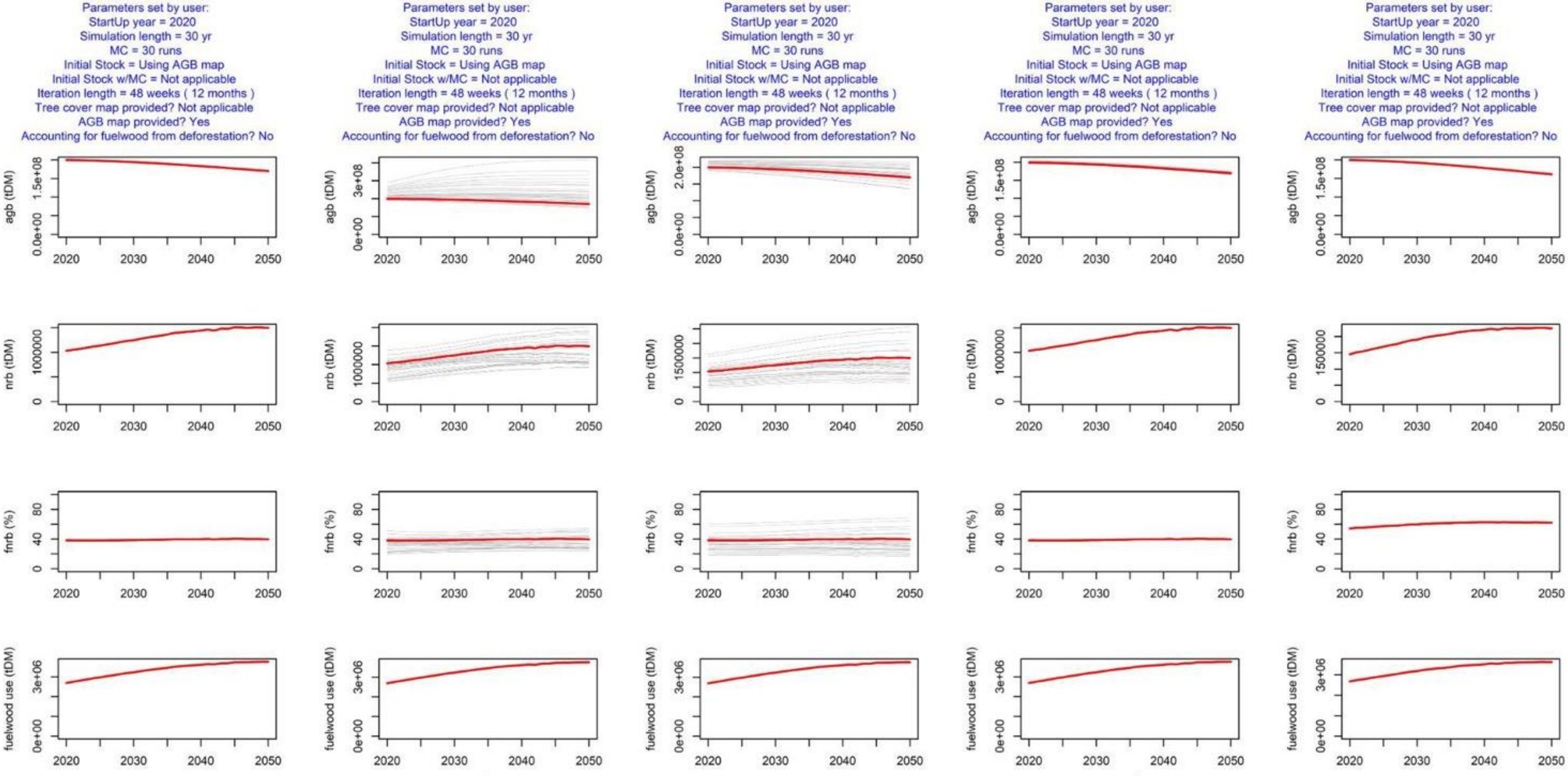
Uncertainty (Monte Carlo simulations)	Uncertainty and sensitivities in MoFuSS
Growth rates and AGB stocks	Growth parameters tables (1 to 3)
Available woody biomass from Trees Outside Forests	Demand scenario (1 to 3)
Stochasticity in harvest patterns– off at global scale	Forest loss & gain (on/off)
	AGB maps (1 to 3)

Figure 20 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).

By comparing the magnitude of values and standard deviations in Table 1, it can be seen that both r_{max-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 20: Trajectories in aboveground biomass, NRB, fNRB, and woodfuel harvest for five MoFuSS settings, for 30 Monte Carlos runs (n=30)



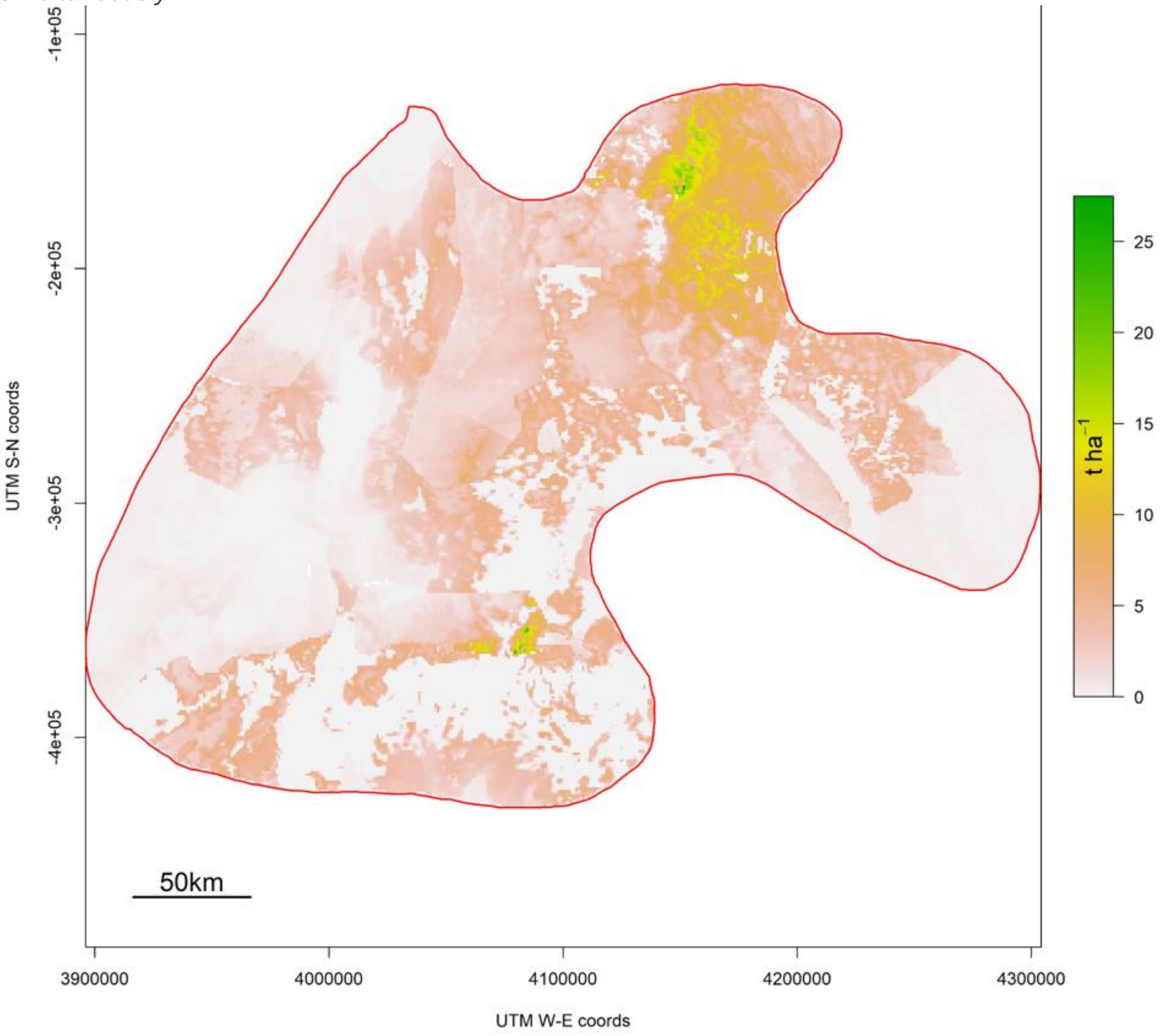
a b c d e

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.

Finally, Figure 21 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.

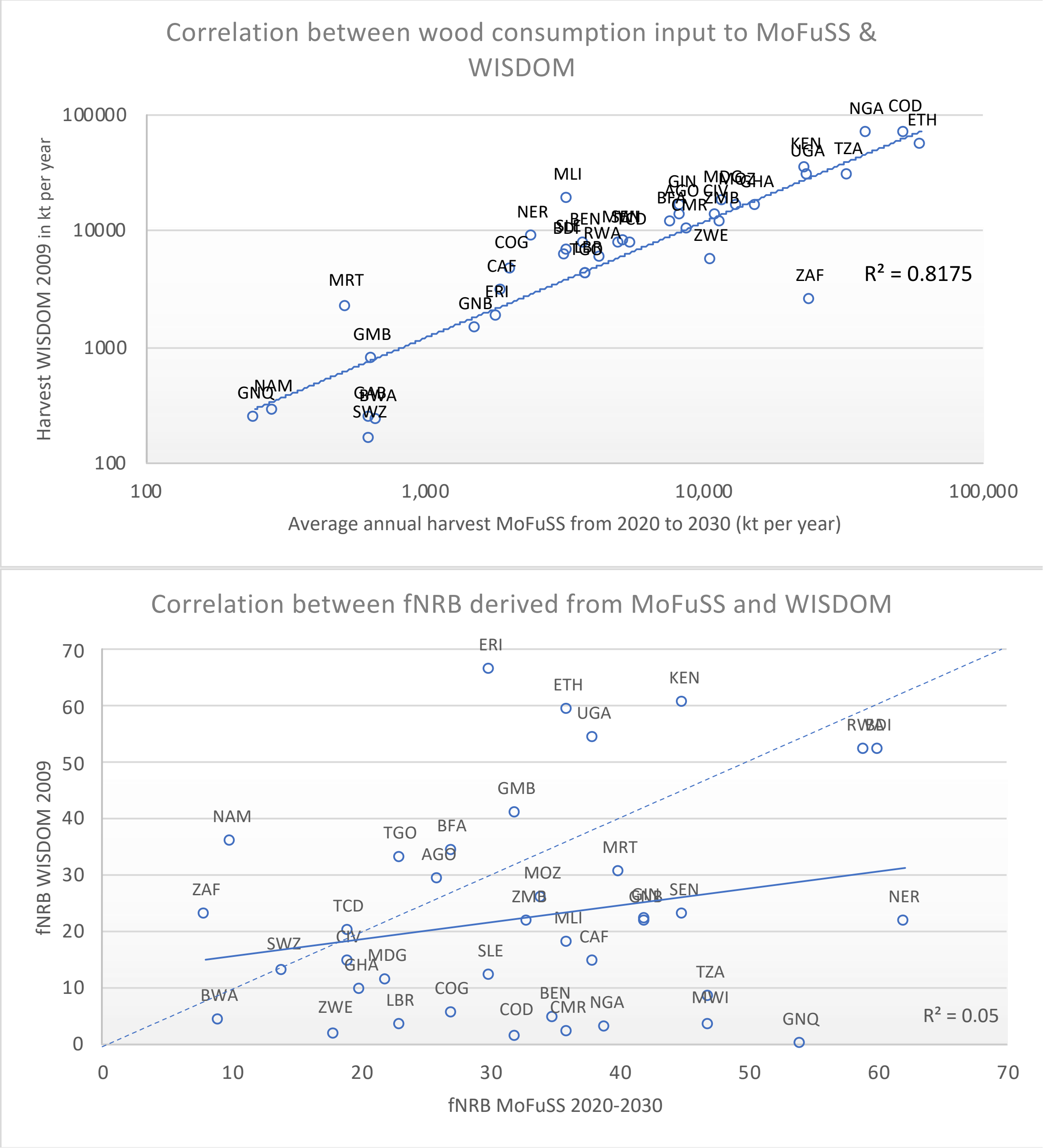
Figure 21: Standard deviation of NRB after 30 Monte Carlo runs allowing all parameters to vary simultaneously.



Comparison with the previous pan-tropical WISDOM study

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 42 countries that overlapped between the two studies. Despite using different assumptions and data sources to estimate woodfuel demand, there is strong correlation between annual woodfuel consumption (Figure 22 - top). However, there is much lower correlation in fNRB derived from each study (Figure 22 – bottom). This study found higher fNRB in two-thirds of the 42 countries in common between the two studies (countries lying to the left and below of the dashed line in the lower plot of Figure 22).

Figure 22: Scatter plot showing input woodfuel demand for MoFuSS and WISDOM (top – log scale) and national fNRB values (bottom – the dashed line shows the line along which results would be equal)



fNRB assessment for other regions

While this study focused on national and sub-national fNRB estimates countries in for sub-Saharan Africa, the terms or reference also included a request to produce “conservative” default values for other regions. We have done this assessment for Central America (including Haiti and the Dominican Republic), South Asia, and SE Asia. Key inputs were identical to the assessment for sub-Saharan Africa descirbed above. However, due to constraints in time and resources, each of these analyses consisted of the following simplifications:

- Shorter simulation periods running only from 2010-2030
- A single pressure map based on 2010 demand rather than annually changing maps, which were used for sub-Saharan Africa
- A single simulation with just one Monte Carlo

In addition, the results have not undergone the same degree of scrutiny from the Methodology Panel as the results from sub-Saharan Africa and should be considered preliminary.

Preliminary results from other regions

Figure 23 shows time series of key results from the three regions for a simulation running from 2010-2030. There are a few interesting differences worth pointing out. For example, woodfuel consumption in Central America is forecast to increase slightly through 2030, while in South Asia, it is forecast to decline rapidly, and in SE Asia, it is also forecast to decline, but more gradually than in South Asia.

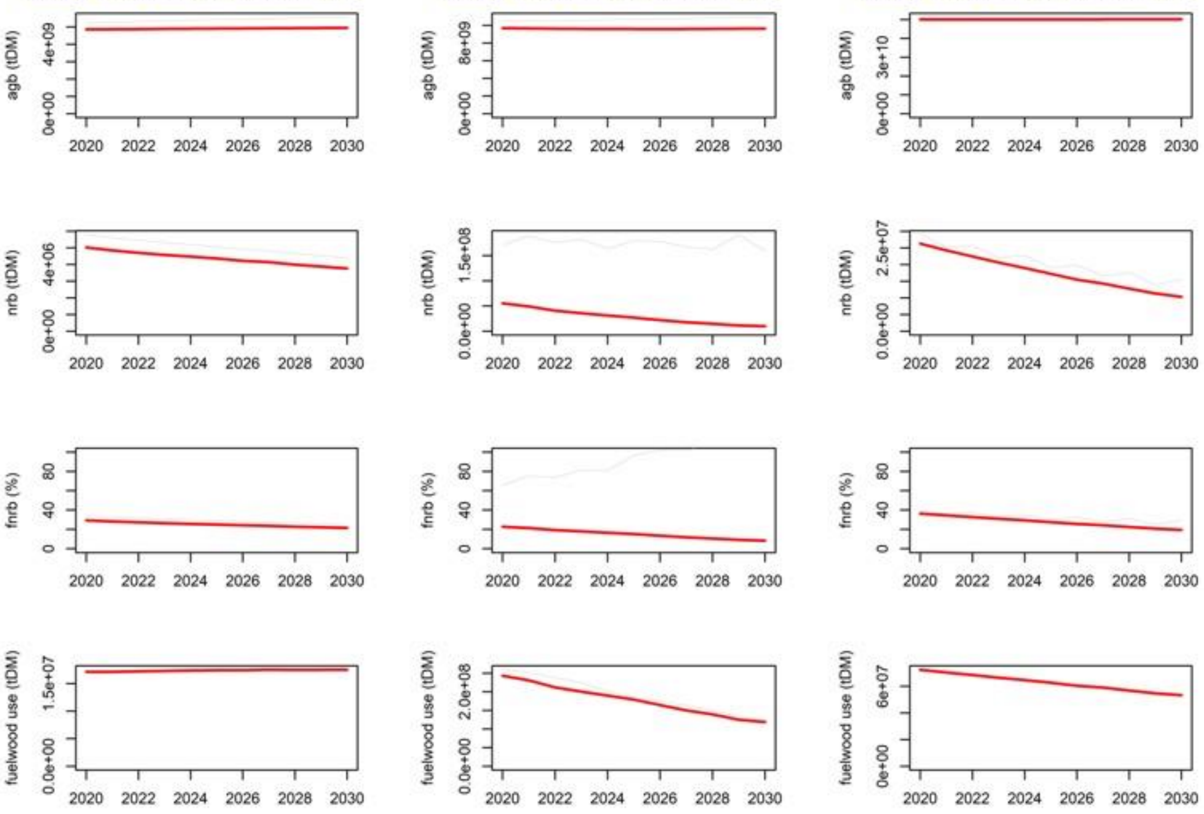
There is there is some unsustainable harvesting in all three regions, resulting in fNRB estimates between 2020 and 2030 ranging from 20-30% in Central America, 10-30% in South Asia, and 20-35% in SE Asia. Time averaged values are given in Table 5.

Table 5: preliminary fRNB estimates for Central America, South Asia and, SE Asia

Region	NRB kt (2010-2030)	Harvest kt (2010-2030)	fNRB (2010-2030)
Central America	108721	355017	31
South Asia	1482834	5333689	28
SE Asia	618982	1551628	40

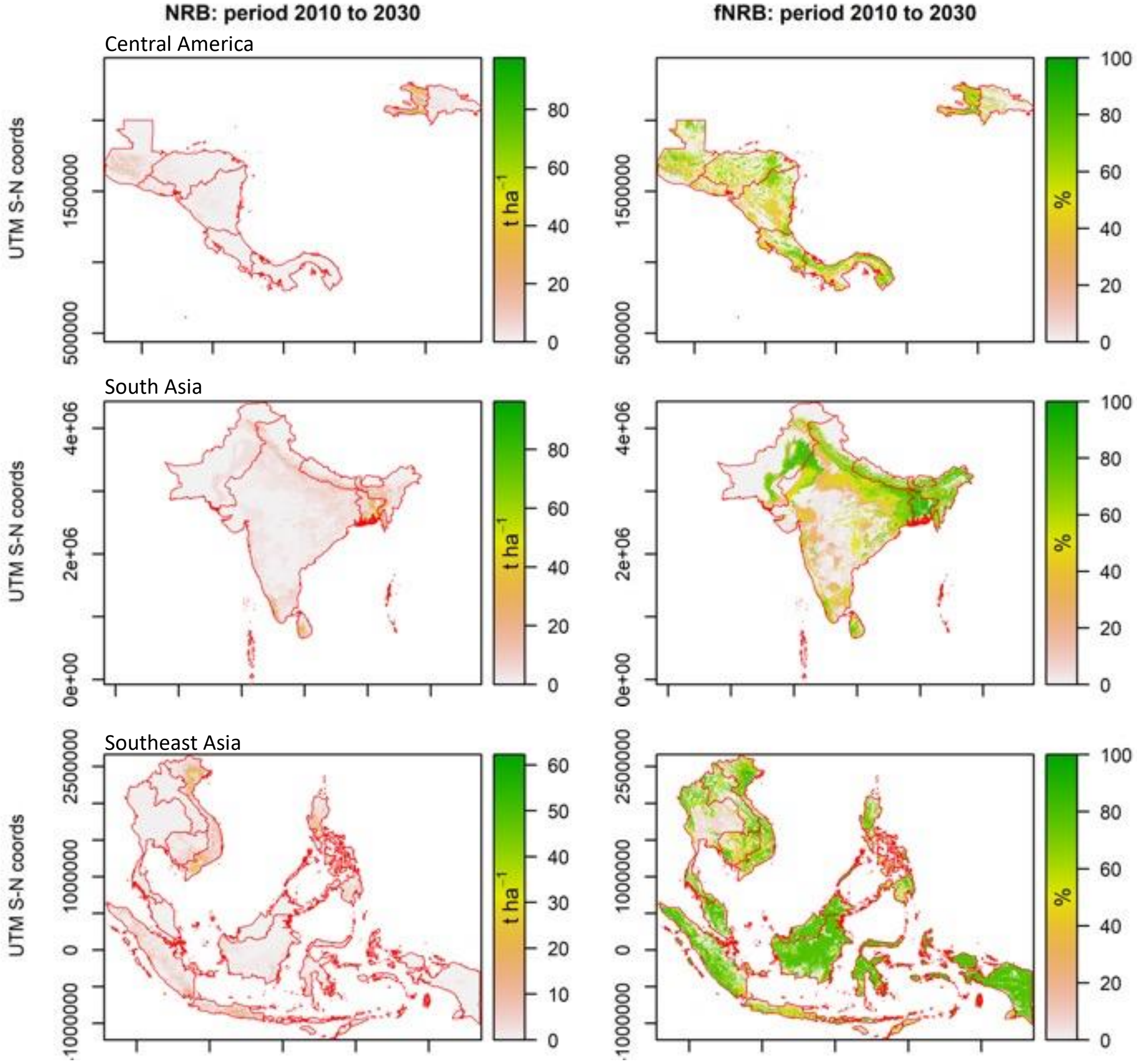
As in sub-Saharan Africa, there is considerable spatial variation within each region. While variation does not come through in the regional default values shown in Table 5, it is apparent from maps of the outputs, which are shown in Figure 24. In Central America, the highest incidence of NRB occurs in Haiti. In South Asia, Western Pakistan, Bangladesh and the Himalayan foothills across northern India and southern Nepal appear to be impacted the worst, and in SE Asia, parts of Vietnam, Indonesia, and the Philippines are impacted. However, these results should be considered preliminary. More analyses are forthcoming, which will result into national and sub-national values for each region.

Figure 23: Preliminary results of regional MoFuSS models for Central America (left), South Asia (center), and Southeast Asia (right).



Central America South Asia Southeast Asia

Figure 24:


NRB: period 2010 to 2030
fNRB: period 2010 to 2030
Central America
South Asia
Southeast Asia
UTM S-N coords
500000
1500000
0e+00
2e+06
4e+06
-1000000
0
1000000
2500000
t ha-1
%
0
20
40
60
80
100
10
30
50

Key background reading

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.

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

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

[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] UNFCCC 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

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

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

[19] 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

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[24] UNDESA 2018 World Urbanization Prospects: 2018 *United Nations, Department of Economic and Social Affairs - Population Dynamics*

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

[30] 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

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

Appendix 1: Accessing Code, datasets, and results

MoFuSS main webpage

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

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.ms 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: *TBD*
Description and usage: These datasets are currently hosted in UNAM's physical storage computing facilities, and are fully available upon request. Biophysical datasets (18.5Gb) + Population and woodfuel use datasets (4.7Gb) + Admin vector datasets (25Gb) + Stock and growth datasets (10.9 Gb).

Key references

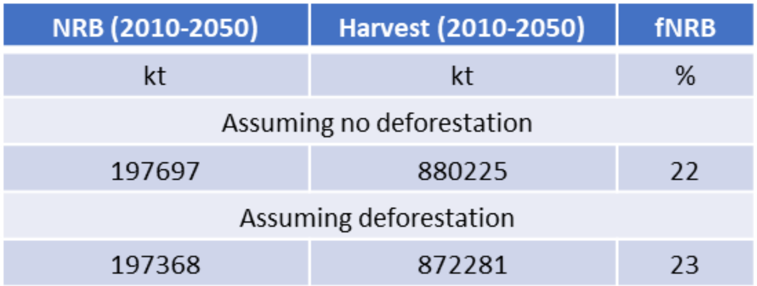
URL: https://is.gd/9R9OjX

Appendix 2: Why was MoFuSS deforestation submodule not used in this assessment?

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.

However, for this global study we ended up turning this feature off due to a variety of reasons. First, it was very difficult to calibrate a single model for an entire continent, and we couldn’t get validation rates higher than 10 or 20% overall. Second, landscape prospective models are intended to be used at a similar resolution as the input data (30 m in this case). Aggregating original 30m data to 1km2 results in weird deforestation patterns as the total amount of deforested area must be maintained at any one resolution but is “concentrated” in fewer areas because of using coarse pixels. Third, the wood that becomes available from deforestation is only available for the year of the event and only within a circumscribed area, i.e. not marketable across far away places or between countries. While this assumption might be wrong for large-scale deforestation, where the felled woody biomass could be indeed commercialized, respond to the fact that MoFuSS was originally designed for landscape level analysis where deforestation is mostly scattered and not driven by agribusiness. Finally, NRB and fNRB results in areas heavily deforested weren’t affected too much, because of the previous points basically (Table 6).

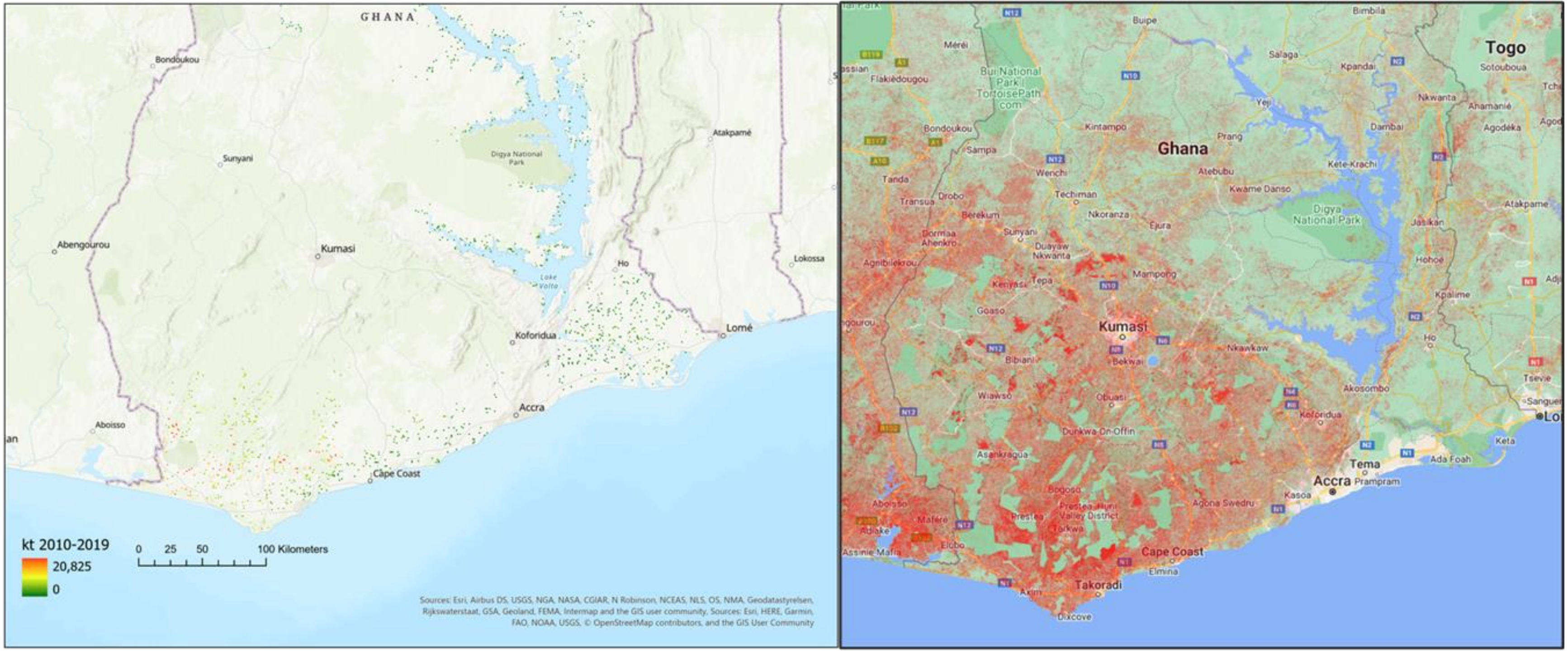
Table 6: Comparison in NRB, harvest and fNRB values for Ghana assuming deforestation versus no deforestation in the simulation period 2010-2050



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 25: 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.

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Document information

Version	*Date*	*Description*
01.0	06 October 2023	MP 92, Annex 7 To be considered by the Board at EB 120.

Decision Class: Regulatory
Document Type: Information note
Business Function: Methodology
Keywords: biomass, calculations, fraction of non-renewable biomass, wood products