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Potential environmental benefits from woodfuel transitions in Haiti: Geospatial scenarios to 2027

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Supplementary material for this article is available [online](#)

Abstract

Woodfuels constitute nearly 80% of Haiti's primary energy supply. Forests are severely degraded and the nation has long been considered an archetypal case of woodfuel-driven deforestation. However, there is little empirical evidence that woodfuel demand directly contributes to deforestation, but may contribute to degradation. We use MoFuSS (Modeling Fuelwood Sustainability Scenarios), a dynamic landscape model, to assess whether current woodfuel demand is as impactful as it is often depicted by simulating changes in land cover that would result if current demand continues unabated. We also simulate several near-term interventions focused on woodfuel demand reduction to analyze the land cover impacts of different energy trajectories. We find that current demand may contribute to moderate levels of degradation, but it is not as severe as is typically portrayed. Under a business-as-usual scenario, the simulated regenerative capacity of woody biomass is insufficient to meet Haiti's increasing demand for wood energy and, as a result, between 2017 and 2027 stocks of above-ground (woody) biomass could decline by $4\% \pm 1\%$. This is an annual loss of 302 ± 29 kton of wood and would emit 555 ± 54 kton $\text{CO}_2 \text{ yr}^{-1}$. Aggressive interventions to reduce woodfuel demand could slow or even reverse woodfuel-driven degradation, allowing woody biomass to recover in some regions. We discuss the policy implications and propose steps to reduce uncertainty and validate the model.

1. Introduction

This study examines woodfuel supply-demand dynamics in Haiti and explores the implications of several near-term household energy pathways for the small island nation. Fuelwood and charcoal represent nearly 80% of the country's primary energy supply [1]. Haiti has long been considered an archetypal case of woodfuel-driven deforestation [2, 3] and popular environmental media have perpetuated this narrative [4–7]. Official reports of forest cover in the country reinforce the notion that Haiti's tree cover is under extreme stress, and that the country has very little forest remaining [8–10]. However, more recent

analyses have raised questions about the accuracy of these assessments. For example, by examining higher resolution images that better capture the patchiness of Haiti's existing tree cover, Churches and colleagues find that forest cover in Haiti could exceed 30% [11], and other analyses support these findings [12, 13]. Recent analyses also indicate that the woody biomass utilized as feedstock for charcoal originates from coppice-based agroforestry systems rather than unmanaged woodlands [14, 15]. These systems are fairly resilient and may represent a sustainable approach to woodfuel provision [16].

While these recent findings encourage us to rethink popular narratives of Haiti's forest cover and the

oft-repeated link between Haiti's charcoal industry and deforestation, analysts still stress that Haiti's forests have been, and remain, severely degraded [11, 14]. Moreover, in the absence of interventions, demand for woodfuels will likely increase, driven by rapid urbanization, which is often accompanied by a shift in residential energy use from fuelwood to charcoal, and a lack of investment in alternative sources of energy [17]. The impacts of increasing demand remain uncertain, and may extend beyond Haiti's borders. For example, numerous sources note that large volumes of Haiti's charcoal originate from the Dominican Republic (DR) [18, 19], which has recently experienced high rates of forest loss [20].

Thus, although the condition of Haiti's forest cover may not be as dire as some analyses have portrayed, there is reason for concern as Haitians attempt to meet their growing demand for energy while avoiding additional forest degradation within their own borders and beyond. Interventions reducing woodfuel demand have been shown to support regeneration in degraded landscapes elsewhere [21]. A set of detailed simulations could indicate where impacts of additional woodfuel demand are likely to be felt, and whether interventions are likely to reduce future impacts. Here we present the results of a study, commissioned by the Global Alliance for Clean Cookstoves (GACC), with financial support from Global Affairs Canada. The analysis contributes to the literature on land use change in Haiti and informs environmental decision-making in the island nation. There are two main objectives:

1. Develop a spatial database to quantify the fraction of non-renewable biomass (fNRB) harvesting attributable to woodfuel demand and identify 'high risk areas' where the current or future sustainability of biomass resource exploitation would be particularly at risk.
2. Develop a series of scenarios examining the potential impacts of Haiti's future charcoal demand. The scenarios simulate how different interventions focused on demand reduction could affect woody biomass and influence fraction of non-renewable biomass (fNRB) throughout the country.

2. Background on charcoal and deforestation in Haiti

Land cover change in Haiti can be traced to the colonial era. Through the 17th and 18th centuries, the French established a slave-based plantation economy that dramatically modified the landscape [22–24]. Hardwood forests were cleared from Haiti's lowland alluvial plains and nearby mountains. Some wood was exported to France and the rest used to meet Haiti's needs for timber and fuel, particularly in the sugar refineries that drove the island's early economy [25].

In the 19th century, a negotiated war indemnity with France was funded through vast timber concessions and settlements across the countryside [15, 26]. In the early 20th century, US Marines occupied Haiti (1919–1934), and expanded bridges and roads into previously isolated parts of the country [14, 27]. Not long after, the US State Department noted there were virtually no commercially valuable timber species left in Haiti [28].

It was around that time that references to charcoal in Haiti begin to appear, after much of Haiti's original forest was cleared [15]. Charcoal demand grew through the 20th century, in tandem with the country's urban population, which was facilitated by the US-built infrastructure [29]. Charcoal for Port-au-Prince was initially produced from dry forests or arboreal fallows around the city. However, over time, fallow periods were shortened or eliminated altogether [30]. Over time, traditional woodlot systems surrounding Port-au-Prince were over-exploited, and production shifted toward the island of La Gonâve, then the northwestern peninsula, and later to the southern peninsula and central plateau [3, 12, 31, 32]. One assessment suggests that by 1980, only 5% of charcoal consumed in Port-au-Prince came from nearby the capital, while the rest came from central Haiti, La Gônave, and the northwestern and southern peninsulas [3]. During that time, many analyses concluded that woodfuel-dependent countries were in 'crisis' [33, 34], including Haiti. One analysis predicted wood supplies would eventually face environmental 'apocalypse' [3]. However, the envisioned 'apocalypse' hasn't occurred and Haitians continue to meet their wood and charcoal demand.

Today, Haiti's charcoal is produced primarily in woodlot systems that are common throughout the countryside. The woodlots contain small, young trees, or coppice from larger tree stumps, with densities ranging from open stands to impenetrable thickets. They are managed on 3–7 year rotations with a combination of active and passive measures. Evidence suggests that this type of coppice system can support a consistent yield for many rotations [15, 16]. Nevertheless, these systems may be degraded if they are harvested at a rate that exceeds their regenerative capacity.

It is important to distinguish between deforestation, which is 'the long-term or permanent loss of forest cover and implies transformation into another land use' and degradation, which is 'the long-term reduction of the overall potential supply of benefits from the forest,' [35, pp 8 and 10]. When deforestation occurs, land cover and land use change from forest to non-forest. This can be visibly detected by remote sensing, but is rarely driven by woodfuel demand [36, 37]. In contrast, forest or landscape degradation is not associated with easily observed land use/land cover change. This analysis simulates degradation by modeling losses in above-ground (woody) biomass or AGB.

3. Methods

3.1. Modeling

Our methodological approach applies spatiotemporal analysis and modeling techniques to publically available data for the entire country utilizing a platform called Modeling Fuelwood Savings Scenarios (MoFuSS—v1.0). The model is an open access platform that is designed to be used by any interested researchers. It consists of several freely available software packages bundled together. Appendix A consists of detailed instructions for downloading, installing and running MoFuSS for any test area within the country of Haiti, with parameters that are tunable through a user-friendly interface; default values correspond to those used in the present study. Beyond reproducing results presented in this study, third party users can open, edit and save all scripts. The model's basic architecture and parameterization are described in a previous publication [38]; hence, we do not provide a detailed description here. However, the model was adapted to accommodate Haiti's specific circumstances, which we discuss below. Table S1 in the supplementary material available at stacks.iop.org/ERL/13/035007/mmedia lists all inputs used in this analysis.

3.2. Definitions of model's key output parameters

We assume changes in AGB during a given time period are a function of four factors: stock remaining after the previous iteration, the maximum growth rate (r_{\max} : the first derivative of a logistic 'S-type' growth curve), maximum biomass density or 'carrying capacity' (K), and consumption during that time period $C_{(t)}$ [38]. Equation (1) describes this relationship:

$$\begin{aligned} \text{AGB}_{(t+1)i} &= \text{AGB}_{(t)i} + \text{AGB}_{(t)i} \cdot \\ & r_{\max} \cdot \left(1 - \frac{\text{AGB}_{(t)i}}{K_i}\right) - C_{(t)i}. \end{aligned} \quad (1)$$

$\text{AGB}_{(t)i}$ and $\text{AGB}_{(t+1)i}$ are above ground woody biomass suitable for fuelwood in pixel ' i ', at time ' t ' and ' $t + 1$ ' respectively. The term ' $\text{AGB}_{(t)i} \cdot r_{\max} \cdot \left(1 - \frac{\text{AGB}_{(t)i}}{K_i}\right)$ ' defines the annual increment of woody biomass; this is always positive, but asymptotically approaches zero as AGB approaches K . $C_{(t)i}$ is woodfuel harvesting that occurs in pixel ' i ' during time-step ' t '. Note AGB may increase or decrease from one time-step to the next depending on the relative magnitudes of $C_{(t)i}$ and $\text{AGB}_{(t)i} \cdot r_{\max} \cdot \left(1 - \frac{\text{AGB}_{(t)i}}{K_i}\right)$.

The factors r_{\max} and K vary with land use/land cover (LULC) categories. In reality they depend on biophysical parameters such as soil, hydrology, insolation, and altitude. Detailed data for these growth parameters is rarely available, particularly in data-poor locations such as Haiti. Lacking empirical data, we define K and r_{\max} based on LULC classifications, matched with empirical data from other locations. These are listed

for each LULC class in table S2 of the supplementary material.

Non-renewable biomass (NRB) is the amount of harvested wood that exceeds natural re-growth over a given time period. In this approach, NRB is defined only in the pixels where AGB declines over time. The ratio of NRB to total woodfuel consumption indicates the fNRB, which indicates the unsustainable proportion of harvested wood.

The model iterates a series of time steps (t) with n -steps per simulation. In this study, $t = 1$ year and $n = 24$ years. There are three primary outputs at each time step: (a) AGB_t , (b) NRB_t (equation 2), and (c) fNRB $_t$, also defined in pixels where decreases in AGB have occurred. For each pixel at time t :

$$\text{NRB}_{(t)} = \begin{cases} \text{AGB}_{(t=0)} - \text{AGB}_{(t)} & \text{if } \text{AGB}_{(t=0)} > \text{AGB}_{(t)} \\ 0 & \text{if } \text{AGB}_{(t=0)} \leq \text{AGB}_{(t)} \end{cases} \quad (2)$$

where $\text{NRB}(t)$ is the amount of fuelwood in tons of dry matter (tDM) which, when harvested, results in a net decrease in AGB between time $t = 0$ and t .

To accommodate uncertainty, the analysis consists of multiple Monte Carlo (MC) simulations (see supplementary material for details). Each MC run generates a different value of $\text{NRB}_{(t=n)}$ by repeating equation 2. $\text{NRB}_{(t=n)}$ is calculated at the pixel-level; it does not account for any increment of AGB occurring in areas where $\text{AGB}_{(t=n)} \geq \text{AGB}_{(t=0)}$. In other words, $\text{NRB}_{(t=n)}$ is defined by AGB loss in pixels where losses occur and are attributable to woodfuel demand. fNRB is calculated as:

$$\text{fNRB}_{(t)} = \frac{\text{NRB}_{(t)}}{C_{(t)}} \quad (3)$$

where C is total residential fuelwood consumption in tDM in time step ' t '. C is input at each iteration so in order to simulate spatio-temporal changes in fuelwood use, which may linked to population growth, demographic change, or energy transitions like the adoption of efficient stoves or alternative fuels.

3.3. Demand

Haiti's residential woodfuel demand was simulated by assigning fractions of different types of cooking fuels utilized in Haitian households based on 2003 census data [39] to a 2003 gridded map of population distribution [40]. Figure S2 shows gridded distribution of population using different types of household fuels, either alone or in combination. Census data indicate the prevalence of woodfuels, but not the quantity used, which is essential to model demand. Per capita charcoal and fuelwood consumption was assumed to be 0.46 and 1.50 kg person day⁻¹ respectively based on a 2007 World Bank report citing older data [19 citing, 41 and 42]. These were used to create a gridded map of combined fuelwood and charcoal demand in 2003 (figure S3 shows a map of aggregate demand in 2003).

Charcoal demand was then converted to dry wood equivalent, assuming an average dry mass yield of 20% (5 tons of dry wood to produce 1 ton of charcoal). This is a typical yield from traditional earthen kilns in many locations around the world [43].

The 2003 census indicates that about 20% of the population used a combination of fuels rather than a single type of fuel—e.g. charcoal with fuelwood or fuelwood with LPG [39]. For these households, we assumed consumption of either charcoal or fuelwood was half that of households using those fuels alone⁵.

3.4. Supply

Wood supply is a function of the quantity and accessibility of woody AGB [38]. Sustainability of the harvest depends on wood productivity. For this assessment, the productivity of woody biomass was based on the most recently available LULC data for Haiti, which provided spatially explicit land cover categories. Each category was then assigned a value for K and r_{\max} as described above. Figure S4 shows the LULC categories used in the analyses. In addition, based on observations in other woodfuel-dependent regions [45], we assume trees outside forests (TOF) provide a sizable fraction of supply, particularly for self-gathered demand. This includes trees on farmland, household compounds, and roadside commons. This wood is accessed by pruning live trees and/or collecting dead/downed branches and is assumed to provide a fixed increment of sustainable supply (up to the value of K defined in table S2). In each locality, the model first utilizes these sources to meet demand, but turns to other sources if demand exceeds the quantity that TOF can supply (see [38] for a full description).

Finally, because a large fraction of harvested wood is utilized for charcoal, the spatial model will be more accurate if it is ‘tuned’ to make production more likely in today’s charcoal producing regions. To do this, the authors carried out a literature review and expert consultation to identify known areas where production is concentrated (see the discussion and figures S5(a)–(b) and S6 in supplemental materials).

3.5. Integration of supply and demand

In order to relate woodfuel consumption at specific points in space and time to supply sites, we project fuelwood and charcoal harvest events based on geographic accessibility, which is a function of proximity to populated areas, transport infrastructure (including transport by boat)⁶, land cover, and elevation (see [38] for a full description). All locations, whether

harvested or not, can accumulate woody biomass (as described in equation 1). If AGB stocks in one location are excessively diminished in one time-step, that location is less likely to be harvested in subsequent time steps until stocks recover. We selected 2003 as the base year of the simulation to align with available demographic data. AGB stocks for 2003, based on LULC categories and forest cover data, are mapped in figure S7. Integrating potential woodfuel supply and demand results in a mapping of harvest pressure for both commercial and self-gathered demand (discussed in more detail in supplemental materials and mapped in figures S8 and S9).

3.6. Scenarios

Scenarios were developed in collaboration with the GACC Haiti team and divided into primarily urban and rural interventions. Scenarios 1–3 project the impacts of large fractions of the urban population shifting away from cooking with solid fuels in traditional devices to either LPG or continuing to use solid fuels, but adopting more efficient stoves (urb_1–3). Scenarios 5–9 focus on rural populations (rur_1–5). Scenarios rur_1–4 mirror the urban transition LPG and ICS. Scenario rur_5 follows a similar pattern but involves a change to non-woody biomass like pellets or briquettes. A final scenario maintains the ‘BAU’ fuel mix, but examines the impacts of widespread use of efficient charcoal kilns (kiln). The transitions are summarized in table 1 below.

We make the following assumptions for each scenario:

- The scenarios cover 2003–2027 and are presented as gridded data disaggregated across Haiti’s 570 communes.
- Population growth is the same under all scenarios and defined by UN population projections (table S3).
- Interventions achieve their targets by growing linearly between from 2017 and 2026 and are applied in proportion to population in all locations.
- The improved charcoal stove reduces fuel demand by roughly 53% when using lump charcoal and 47% when using briquettes or pellets based on different calorific values of the two fuels.
- Briquettes and pellets are derived entirely from agricultural waste and has no impact on land cover.
- Improved charcoal kilns result improve conversion efficiency by 100% (we assume traditional earth-mound kilns are ~20% efficient and improved retort kilns introduced are 40% efficient)⁷.

⁵ The 2003 census lacked data on households using charcoal in combination with LPG; however, we assumed that it was ~6% of the population which matched a later dataset [e.g. 44].

⁶ Historical sources note that transport of firewood and charcoal to Port au Prince was common [46]. While these refer to past observations, one author (AT) notes that this method of transport is still common at the time of writing.

⁷ Efficiencies are defined as the ratio of the mass of charcoal output to the mass of oven-dry wood input. The values are indicative of efficiencies reported by several studies and reviewed in [41, 47–49].

Table 1. Scenario characteristics describing potential transitions.

Name	Description—between 2017 and 2027...	Woodfuel users adopting LPG	Woodfuel users adopting ICS	Woodfuel users adopting briquettes or pellets	% of charcoal produced in improved kilns	No change
urb_1	A fraction of urban woodfuel users shift to LPG and improved charcoal stoves	70%	20%	0%	0%	10%
urb_2		50%	20%	0%	0%	30%
urb_3		25%	50%	0%	0%	25%
rur_1	Same as s_1a, but in rural areas	70%	20%	0%	0%	10%
rur_2	A fraction of rural woodfuel users shift to LPG and improved wood and charcoal stoves	30%	40%	0%	0%	30%
rur_3		10%	60%	0%	0%	30%
rur_4	30% of rural woodfuel users adopt LPG and 40% briquettes or pellet fuels	30%	0%	40%	0%	30%
rur_5	10% of rural fuelwood users adopt LPG and 60% adopt improved woodstoves; no change in charcoal use	10%	60%	0%	0%	30%
kiln	No change in household fuel but 50% penetration of improved charcoal kilns	0%	0%	0%	50%	50%

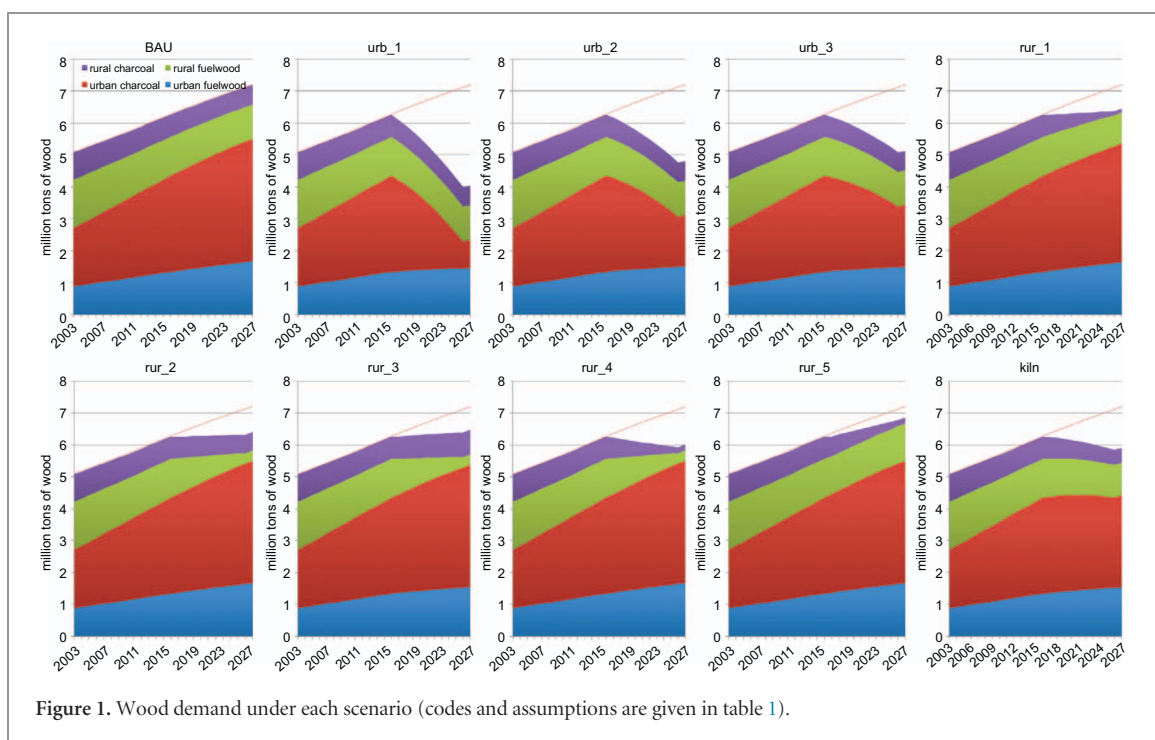


Figure 1. Wood demand under each scenario (codes and assumptions are given in table 1).

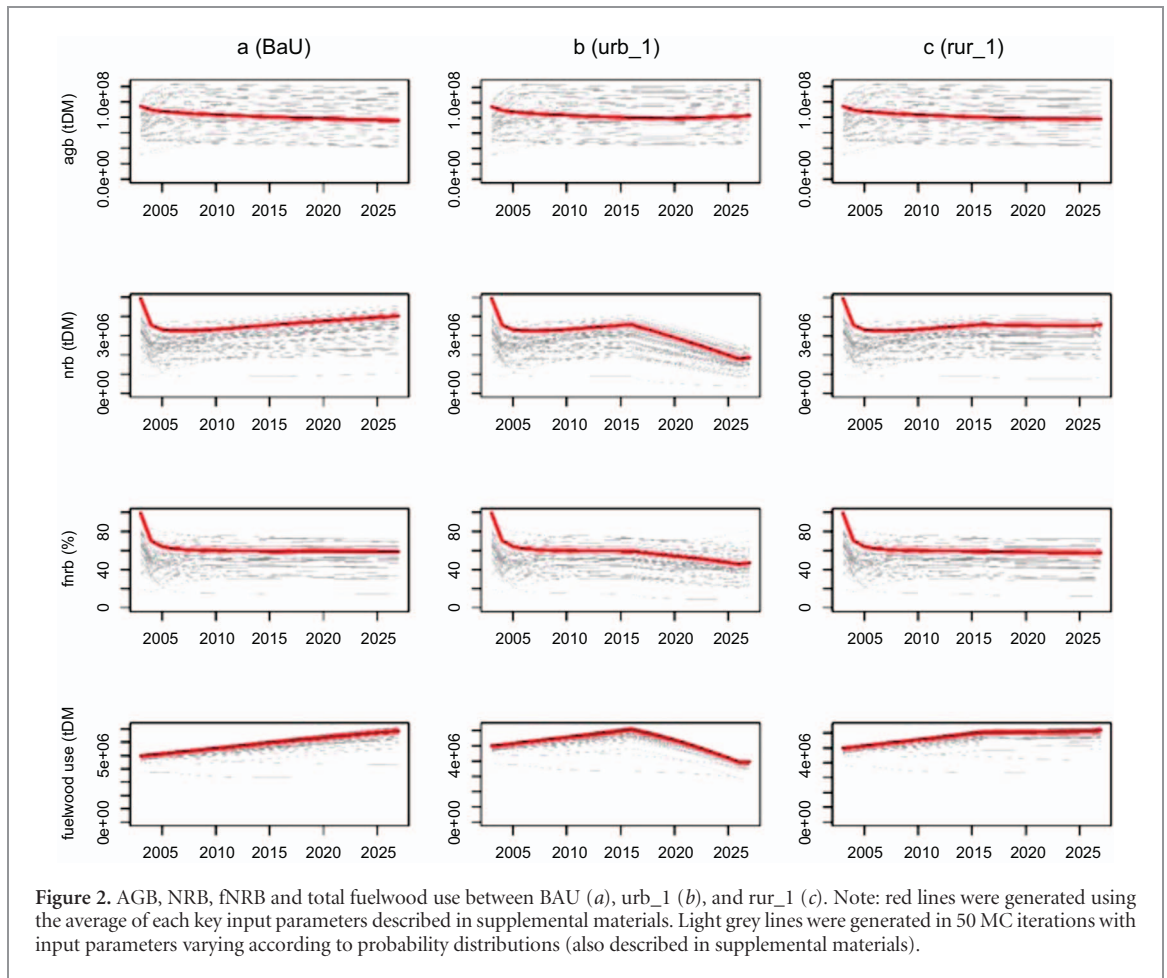
The scenarios result in wood demand reductions ranging from 4% (rur_5) to 60% (urb_1). Demand trajectories disaggregated by location and fuel type are shown in figure 1. Urban-focused scenarios have a larger impact on wood demand than rural scenarios because urban interventions reach larger populations and affect higher proportions of charcoal users.

Several scenarios show an uptick in wood demand between 2026 and 2027 because the interventions are implemented over a 10 year period from 2017–2026. Thus, while technologies remain in use, the adoption of new technology ceases to grow in the final year of the simulation and increases in demand due to population growth are no longer offset. This leads to a small increase in demand in that final year, which would

continue if we extended the scenarios further into the future with no new interventions.

4. Results

Figure 2 compares results from the BAU, urb_1 and rur_1 simulations. Bold red lines show how AGB, NRB, fNRB, and fuelwood demand evolve when mean values for key parameters are used; light gray lines show results for iterations of the 50 Monte Carlo simulations. This discussion focuses mainly on urb_1 because it represents the most extreme reduction in wood-fuel demand (figure 1). Results of other scenarios are shown in table S4 and figure S10. The initial high



value and steep drop in NRB and fNRB between 2003 and 2005 are artifacts of the model parameterization and do not reflect actual conditions.

Our results indicate that under BAU conditions, woodfuel demand leads to the cumulative harvest of 13–19 million tons of NRB over the simulation period, leading to a loss of 3%–20% of AGB, which is apparent by the downward trend in AGB shown in figure 2(a) (top left). Overall demand for woodfuel during the simulation varies from 130–150 million tons, resulting in fNRB of $12\% \pm 2\%$ (mean \pm standard deviation). Under scenario urb_1, annual woodfuel demand drops to 44% of BAU by 2027. This leads to a 6%–11% decrease in cumulative wood harvest over the entire simulation period, 41% reduction in cumulative NRB extraction, and a reversal in the loss of AGB, which is evident in the upward trend in AGB in the latter years of the simulation (figure 2(b)). Scenario rur_1, which is similar to scenario urb_1, but implemented in rural areas, has less dramatic results. Figures 3 and 4 show maps of AGB, NRB and fNRB for BAU and urb_1 respectively.

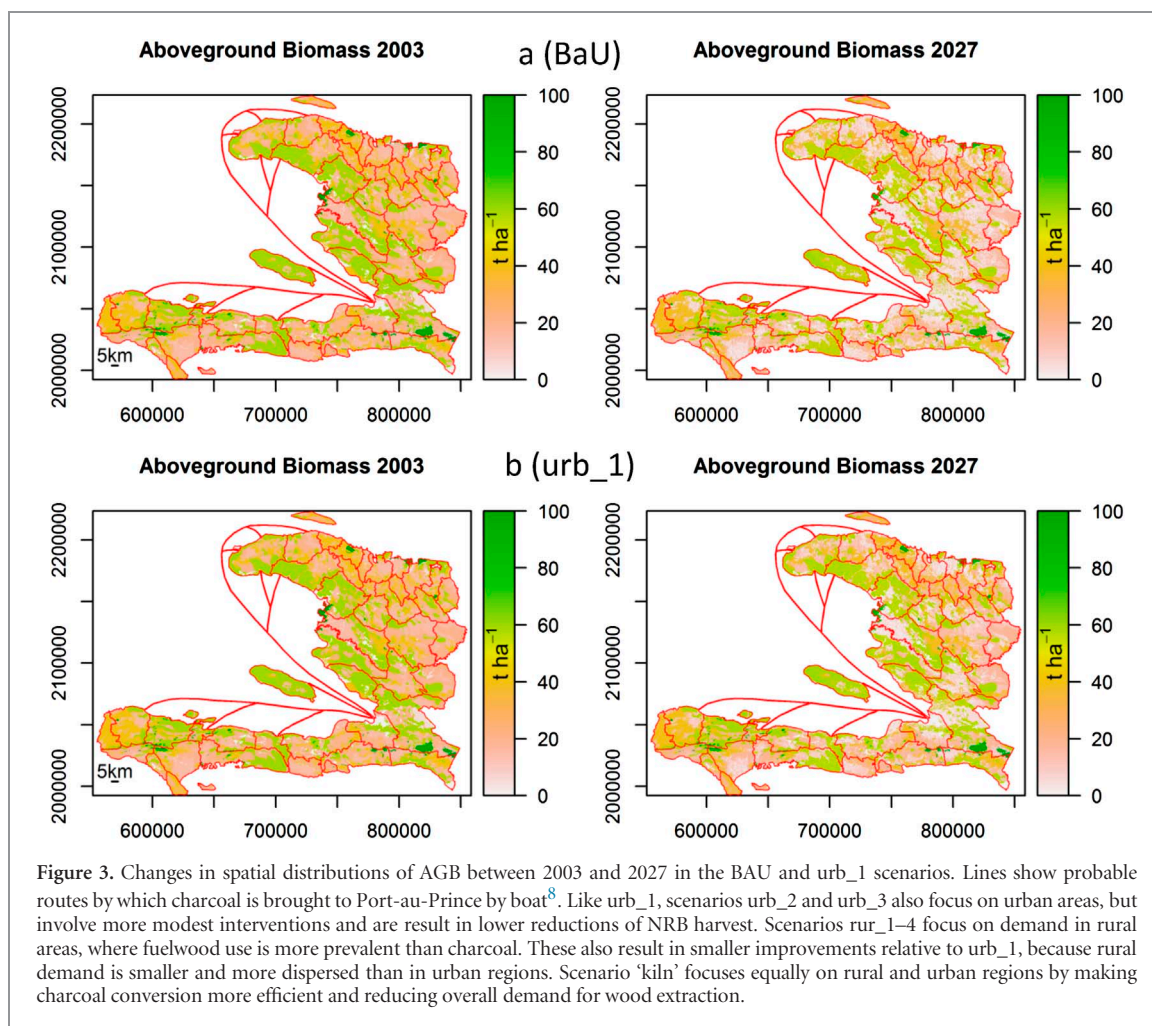
The spatial approach is useful because it allows us to identify areas that are likely to feel the greatest impact from future woodfuel demand (maps are shown in figures S11 and S12). The largest NRB extraction is likely to occur in the *arrondissements* immediately adjacent to Port-au-Prince (*Croix-Des-Bouquets* and *Arcahaie*

to the north and rural parts of Port-au-Prince to the south). There are also concentrations of NRB extraction in *arrondissements* further afield, such as *Gonaives*, *Dessaline*, and *Saint-Marc* to the north, as well as the *Miragoane* and *Aquin* in the southern peninsula. With urb_1, NRB is still extracted from these regions, but volumes are reduced substantially relative to BAU.

Net impacts of each intervention can be visualized by mapping differences in conditions between the BAU and each scenario in the final year of the intervention. Figures 5 and 6 show the differences in standing AGB and harvested NRB between BAU and urb_1 respectively. Naturally, the largest changes are concentrated in those areas most impacted in the BAU scenario. Figure S13 shows the difference in NRB off take for all scenarios. Reductions in the amount of NRB harvested result in downward shift of fNRB from 9%–6% by 2027. Figure 7 illustrates the spatial distribution of changes in fNRB between BAU and urb_1.

5. Discussion and conclusions

Our simulations show that under a reasonable set of assumptions about woody biomass growth and harvest, Haiti will likely experience levels of fNRB that are much lower than other assessments report [50]. These results support recent analyses that argue for a

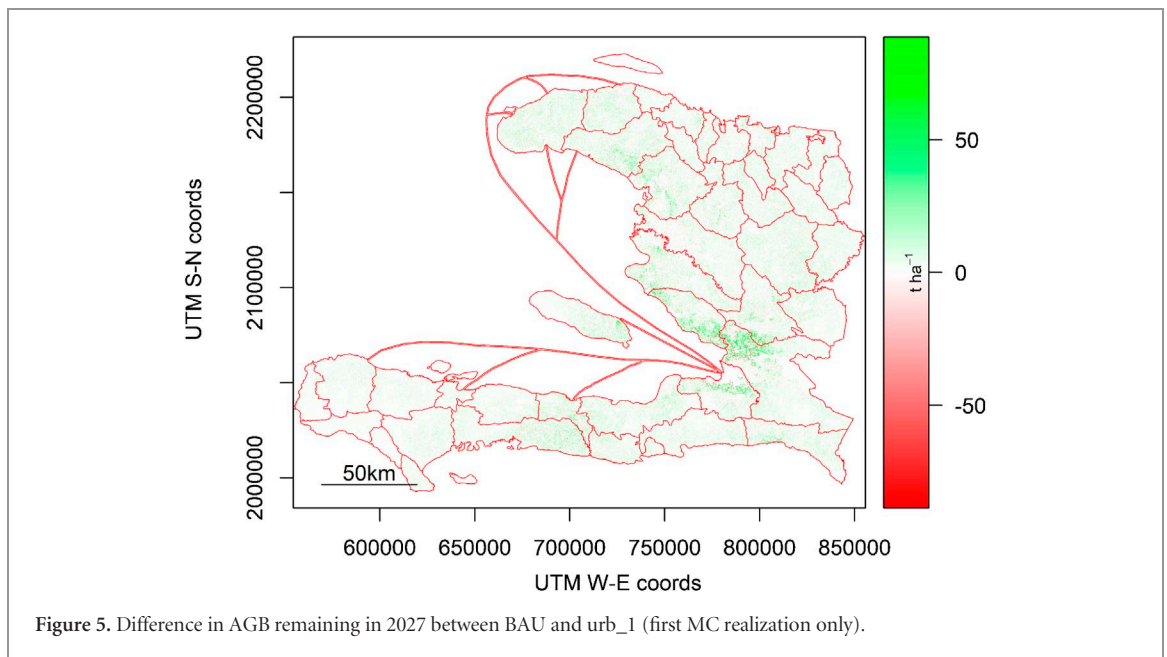
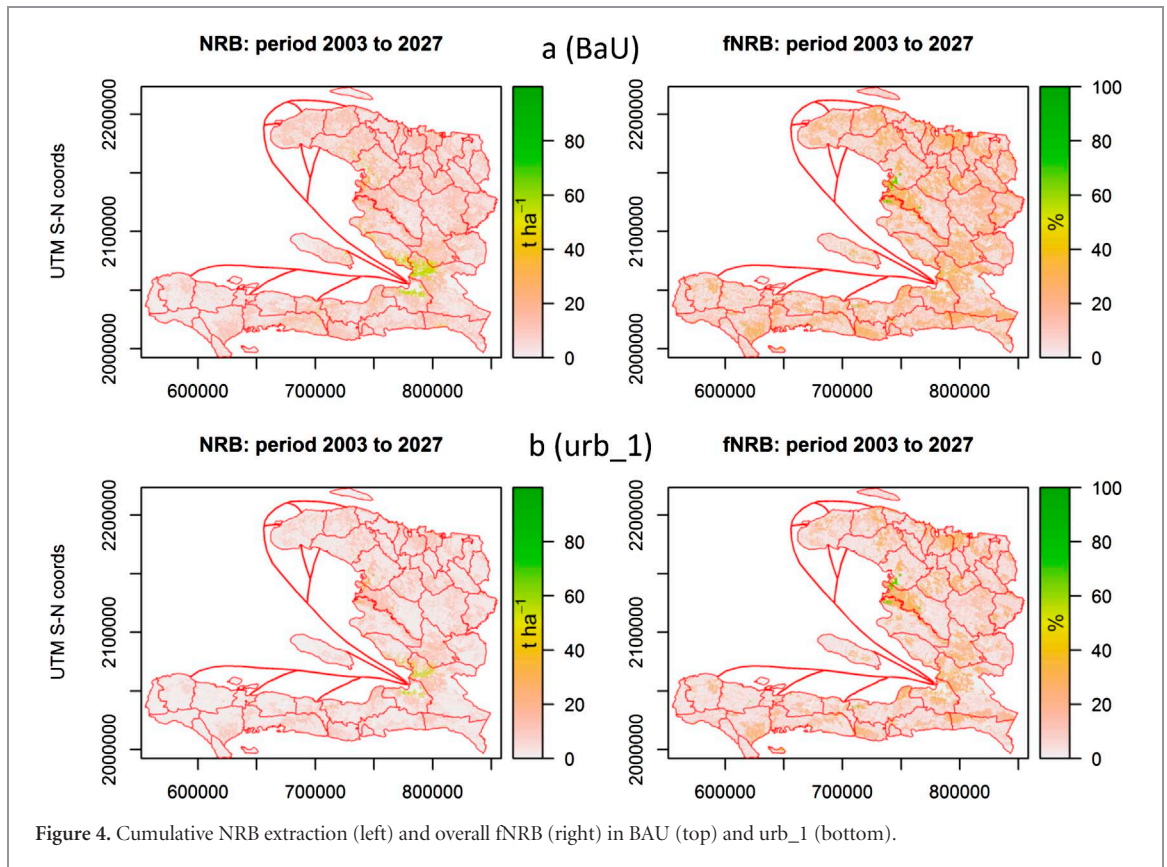


less alarmist view of the relationship between deforestation and woodfuel demand in Haiti. Nevertheless, we do find that under a business-as-usual (BAU) scenario, the estimated regenerative capacity of existing woody biomass resources is insufficient to fully satisfy Haiti’s increasing demand for wood energy without additional degradation of standing biomass. This will result in the annual loss of 302 ± 29 kton of AGB (mean \pm 95% confidence interval) and emit 555 ± 54 kton of $\text{CO}_2 \text{ yr}^{-1}$ over the next decade. These impacts would be lessened if interventions to reduce woodfuel demand were successfully implemented. Interventions result in different levels of mitigation depending on the intensity of effort. Generally, scenarios focused on urban consumers are more effective than scenarios focused on rural consumers, with the exception of rur_4, which simulates the impact of rural households undergoing a large-scale shift away from both wood and charcoal. Under the most aggressive scenarios (urb_1–3 and rur_4), degradation could actually be reversed, allowing AGB stocks to recover slightly by the end of the simulation. Scenarios targeting rural households result in smaller changes and may lead to little

or no improvement at a national scale (e.g. scenarios rur_1–3 and 5 shown in figure S11).

Of course, the input parameters utilized in this preliminary exploration carry large uncertainties. Some of the uncertainty, like biomass stock and growth, are explicitly included via the MC simulations and are explicit in the range of uncertainty shown in our results (table S4 and figure S13). However, other sources of uncertainty are omitted from the analysis because data is simply not available. For example, anecdotal evidence indicates that there is *some* flow of charcoal between Haiti and neighboring DR. If sufficiently large, this flow would affect the results of this analysis by transferring pressure on woody biomass across the border. If data were available, this trade could easily be modeled; however, it was omitted because there is simply no credible estimate of the magnitude or exact destination of charcoal coming from DR to Haiti. Other sources of uncertainty include commercial and industrial demand for woodfuels. If demand from these sectors is sufficiently large and growing at a similar rate as residential demand, it would increase pressure on Haiti’s woody biomass and lessen the impact of interventions limited to the residential sector. In addition, other factors like extreme weather events, which are difficult to model, can play an important role in land

⁸ Boat routes are based on previous maps of sea routes for charcoal arriving in Port au Prince [43].



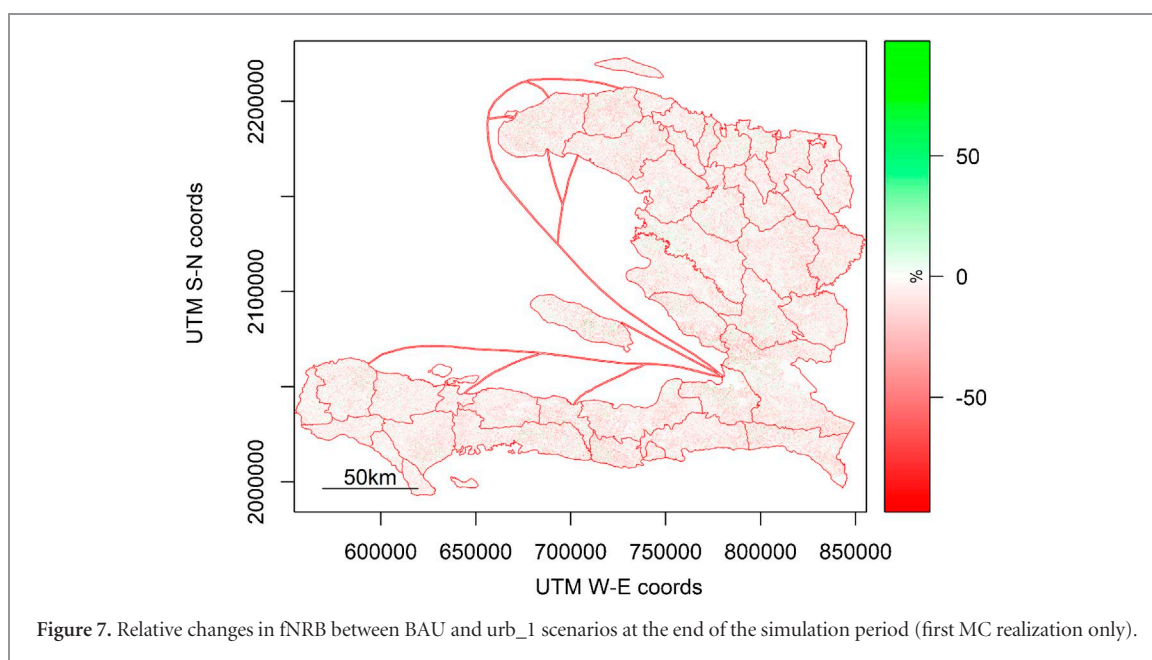
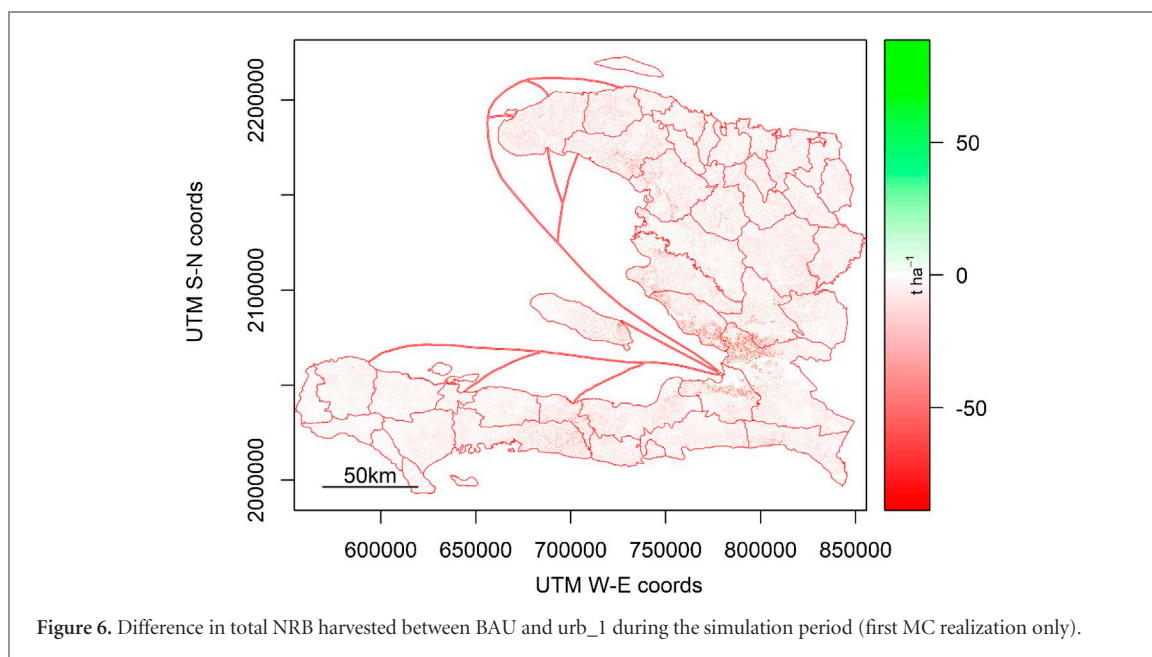
cover change and woody biomass supply. For example, Hurricane Matthew devastated Haiti's southern peninsula in 2016. That year, tree cover loss on the peninsula was 1200% higher than the annual average over the previous decade [20]. While it hasn't been studied in detail, anecdotal evidence indicates that trees felled by the storm were used for charcoal [51].

Last, it is important to recognize the role that charcoal plays in the Haitian economy. Data is limited, but one source notes that charcoal was responsible

for 16% of rural income in the 1990s [19]. Any policies designed to reduce demand for charcoal should also implement measures to avoid negative impacts on rural livelihoods that such policies could have.

6. Future research

The authors are currently securing funding to implement a more in-depth study, including fieldwork



intended to reduce the uncertainties in key inputs described above. For example, to reduce uncertainty in supply parameters, we intend to improve our characterization of the coppice-based agroforestry systems that are thought to contribute much of the country's charcoal feedstock through field-based assessments of on-farm tree growth and management practices. Better understanding of current production would open the possibility of first simulating and later designing policies promoting supply enhancement through intensive agro-forestry or silvicultural interventions.

Future plans also include developing new, supervised land cover classification in order to improve assessments of Haiti's current and future supply of woody biomass. In addition, to further refine the model's supply parameters, we intend to investigate the magnitude of Haiti's cross-border charcoal trade with

DR and work with other researchers to obtain updated sector-specific woodfuel consumption data.

Finally, when modeling policy interventions, it is common practice to test the validity of models by running simulations that begin in the past and end in the near future. This allows for comparison of mid-point results of the simulations to current data. However, simulations may predict small changes in land cover that are not discernable from low- to medium-resolution satellite imagery. Thus, either field work or access to very high resolution images are needed for validation ([19], citing the results of a 1995 survey). In the next phase of research, the authors will use remote sensing techniques to quantify forest degradation in 'hotspots' forecast by the model (i.e. places where the model predicts significant degradation from woodfuel harvesting).

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References

- [1] IEA 2015 *Energy Balances of Non-OECD Countries: 2015* (Paris: International Energy Agency)
- [2] Stevenson G G 1989 The production, distribution, and consumption of fuelwood in Haiti *J. Dev. Areas* **24** 59–76
- [3] Voltaire I 1979 *Charcoal in Haiti* (Port-Au-Prince: USAID/Haiti) p 36
- [4] Diamond J M 2005 *Collapse: How Societies Choose to Fail or Succeed* (New York: Viking Penguin)
- [5] Auch J 2014 Wasteland—Charcoal in Haiti
- [6] Cobb C 1987 Haiti: against all odds *Natl Geo.* **172** 645–70
- [7] Gronewold N 2009 Environmental destruction, chaos bleeding across border *GreenWire* (Washington, DC: E&E)
- [8] FAO 2000 *Global Forest Resources Assessment 2000* (Rome: UN Food and Agriculture Organization)
- [9] FAO 2005 *Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management* (Rome: UN Food and Agriculture Organization)
- [10] FAO 2010 *Global Forest Resources Assessment 2010* (Rome: UN Food and Agriculture Organization)
- [11] Churches C E *et al* 2014 Evaluation of forest cover estimates for Haiti using supervised classification of Landsat data *Int. J. Appl. Earth Obs. Geoinf.* **30** 203–16
- [12] Tarter A 2016 Haiti is covered with trees *Environ. Society* (www.envirosociety.org/2016/05/haiti-is-covered-with-trees/)
- [13] Álvarez-Berrios N *et al* 2013 Land change in the greater Antilles between 2001 and 2010 *Land* **2** 81
- [14] Tarter A M *et al* 2016 *A History of Landscape-Level Land Management Efforts in Haiti* (Washington, DC: World Bank) p 77
- [15] Tarter A 2015 Adaptive arboreal practices: Haitian farmer responses to on-going deforestation *Department of Anthropology* (Gainesville FL: University of Florida)
- [16] Pasiecznik N *et al* 2001 *The Prosopis juliflora—Prosopis pallida Complex: A Monograph* (Coventry, UK: HDRA) p 172
- [17] USAID 2017 *Where We Work* (Washington, DC: USAID)
- [18] Kheel J 2014 *The Charcoal War* (latinamericanscience.org)
- [19] ESMAP 2007 *Haiti: Strategy to Alleviate the Pressure of Fuel Demand on National Woodfuel Resources* (Washington, DC: Energy Sector Management Assistance Program)
- [20] Hansen M C *et al* 2017 *Hansen/UMD/Google/USGS/NASA Tree Cover and Tree cover Loss and Gain, Country Profiles* (University of Maryland, Google, USGS, and NASA)
- [21] Agarwala M *et al* 2017 Impact of biogas interventions on forest biomass and regeneration in southern India *Glob. Ecol. Conserv.* **11** 213–23
- [22] Lindskog D P 1998 From Saint Domingue to Haiti: some consequences of European colonisation on the physical environment of Hispaniola *Caribbean Geogr.* **9** 71–86
- [23] Moya Pons F 2007 *History of the Caribbean: Plantations, Trade, and War in the Atlantic World* (Princeton, NJ: Markus Wiener Publishers)
- [24] Tarter A *et al* 2016 *A History of Landscape-level Land Management Efforts in Haiti: Lessons Learned from Case Studies Spanning Eight Decades* (Washington, DC: World Bank Press)
- [25] Catanese A 1999 *Haitians: Migration and Diaspora* (Boulder, Colorado: Westview Press)
- [26] Bulmer-Thomas V 2012 *The Economic History of the Caribbean Since the Napoleonic Wars* (Cambridge: Cambridge University Press)
- [27] Leyburn J G 1998 *The Haitian People With a new introduction by Bryant C Freeman* (Lawrence: Institute of Haitian Studies, University of Kansas)
- [28] Klein M A 1945 *Forest Conditions in Haiti: A Special Report* (Washington, DC: The Institute of Inter-American Affairs, Food Supply Division)
- [29] White T A 1994 Policy lessons from Haiti and natural resource projects in rural Haiti *Environmental and Natural Resource Policy and Training (EPAT) Project, Midwestern Universities Consortium for International Activities* (Madison, MN: University of Minnesota)
- [30] Murray G F 1977 *The Evolution of Haitian Peasant Land Tenure: a Case Study in Agrarian Adaptation to Population Growth* (New York: Columbia University)
- [31] Conway F J 1979 *A Study of the Fuelwood Situation in Haiti* (Washington, DC: USAID)
- [32] Smucker G R 1981 *Trees and Charcoal in Haitian Peasant Economy: A Feasibility Study of Reforestation* (Washington, DC: USAID)
- [33] de Montalembert M R and Clement J 1983 Fuelwood supplies in the developing countries *FAO Forestry Paper* (Rome: UN Food and Agriculture Organization)
- [34] Eckholm E 1975 *The Other Energy Crisis: Firewood* (Washington, DC: Worldwatch) p 22
- [35] Schoene D *et al* 2007 Definitional issues related to reducing emissions from deforestation in developing countries *Forests and Climate Change Working Paper* (Rome: UN FAO) p 29
- [36] Geist H J and Lambin E F 2002 Proximate causes and underlying driving forces of tropical deforestation *BioScience* **52** 143–51
- [37] Hosonuma N *et al* 2012 An assessment of deforestation and forest degradation drivers in developing countries *Environ. Res. Lett.* **7** 044009
- [38] Ghilardi A *et al* 2016 Spatiotemporal modeling of fuelwood environmental impacts: towards an improved accounting of non-renewable biomass *Environ. Modell. Softw.* **82** 241–54
- [39] Institut Haïtien de Statistique et d'Informatique Républicaine d'Haïti 2003 *Recensement General de la Population et de l'Habitat République d'Haïti* Ministère de l'Economie et des Finances: Minnesota Population Center at the University of Minnesota—Microdata Series, International census microdata for social and economic research IPUMS-International
- [40] Azar D *et al* 2010 Spatial refinement of census population distribution using remotely sensed estimates of impervious surfaces in Haiti *Int. J. Remote Sens.* **31** 5635–55
- [41] ESMAP 1991 *Haiti-Household Energy Strategy* (Washington, DC: Energy Sector Management Assistance Programme (ESMAP) of the World Bank) p 184
- [42] Matly M 1990 Energy strategy for the residential sector and small businesses *Energy Sector Management Assistance Programme* (Washington, DC: World Bank)
- [43] Bailis R 2009 Modeling climate change mitigation from alternative methods of charcoal production in Kenya *Biomass Bioenergy* **33** 1491–502
- [44] Asner G P *et al* 2010 High-resolution forest carbon stocks and emissions in the Amazon *Proc. Natl Acad. Sci.* **107** 16738–42
- [45] Bailis R 2004 *Encyclopedia of Energy* ed Cleveland C J (New York: Elsevier) pp 509–26
- [46] CNIGS 2012 *Haiti Populated Places and Toponyms* (Port-au-Prince: Haitian National Centre for Geospatial Information)
- [47] Grosenick G and McGowan L 1986 *Determining the Consumption of Wood Products in Port-au-Prince Using Supply Surveys* (University of Maine Agroforestry Outreach Research Project)

- [48] UNDP/ESMAP 1982 *Haiti: Issues and Options in the Energy Sector* (Washington, DC: UNDP/ESMAP) p 101
- [49] Nexant Inc. 2010 *Final Report: Assessment of Haiti Alternative Cooking Technologies Program* (Washington, DC: USAID) p 125
- [50] Bailis R *et al* 2017 Getting the numbers right: revisiting woodfuel sustainability in the developing world *Environ. Res. Lett.* **12** [115002](#)
- [51] McFadden D 2017 *Pervasive Charcoal Trade Getting Major Rethink in Haiti* (New York: Associated Press)