

Geospatial Mapping of Charcoal and Fuelwood Renewability in Haiti and Potential Environmental Benefits from Woodfuel Interventions

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Abstract

This analysis examines woodfuel sustainability in Haiti and explores the impacts of near-term household energy interventions. Woodfuels represent nearly 80% of the Haiti's primary energy supply and the country has long been considered an archetypal case of woodfuel-driven deforestation. However, recent analyses have questioned whether woodfuel demand is as impactful as it is often portrayed. We present the results of a study that 1) quantifies non-renewable biomass (NRB), 2) identifies "high risk areas" where biomass sustainability is a major concern, and 3) examines the impacts of nine of interventions focused on woodfuel demand reduction.

We accomplish this by developing a series of computer simulations using the MoFuSS methodology. MoFuSS (Modeling Fuelwood Sustainability Scenarios), was developed as a tool to analyze landcover change induced by woodfuel demand. This assessment ran simulations between 2003 and 2027, with interventions starting in 2017. Results show that under a business-as-usual (BAU) scenario, existing woody biomass resources are insufficient to meet Haiti's increasing demand for wood energy. We project that stocks of above-ground (woody) biomass (AGB) will decline by 3-20% by 2027. This represents an annual loss of 100,000-800,000 tons of wood from the landscape, which is equivalent to 0.2-1.5 million tons of CO₂/yr.

Our simulations show that these impacts would be lessened if interventions to reduce woodfuel demand were successfully implemented over the next decade. In the most aggressive scenario, woodfuel demand declines by ~44% by 2027, which leads to an

overall reduction in wood harvesting of 6-11% relative to BAU, a 41% reduction in NRB, and stabilize projected declines in AGB. Other, more modest scenarios would show similar, but less dramatic results.

In addition, while all of the woodfuel demand-reduction measures reduce NRB extraction and slow or stop Haiti's gradual loss of AGB, the current results include a wide range of uncertainty. Key parameters like the magnitude of charcoal imports from the Dominican Republic, the extent to which trees outside forests are utilized for charcoal and their productivity, and the accuracy of the land-use land cover data are not well characterized. In order to narrow the uncertainty and better understand the potential benefits of interventions, we propose several steps including consultations with additional experts within Haiti and a targeted fieldwork.

Abbreviations and Definitions

- AGB (aboveground woody biomass): Not all AGB is usable as fuelwood or for charcoal making, however, at this stage we assume all AGB to be usable as wood energy as we found no data yet. For comparison, about 90% of AGB is usable for charcoal making in oak forests in central Mexico (Aguilar, Ghilardi et al. 2012).
- DBH (diameter at breast height): a common measure of tree girth used to assess woody biomass stock and growth.
- fNRB (fraction of non-renewable biomass): The ratio of NRB (defined below) to total fuelwood use in a given locality. This describes the extent to which harvesting of wood is unsustainable.
- Forest: We define forest or "forest cover" broadly, to include sparse and mosaic woodlands and rangelands not necessarily classified as "forest" under more conventional definitions which use thresholds for canopy cover or tree height.
- Fuelwood, also known as firewood: Woody biomass used as an energy source without any thermochemical transformation and with little or no mechanical processing.
- ICSs (improved cookstoves): Efficient end-use cooking devices using less fuel and emitting fewer pollutants in comparison to traditional (i.e. less-efficient) models. It is used interchangeably with efficient or fuel-saving cookstoves.
- IDW (Inverse Distance Weighted).
- K (carrying capacity): Maximum achievable AGB stock given a certain class of Land Use and Land Cover, plus any other biophysical constraints. K is assumed to remain constant in time within NRBv1.0Mofuss.
- LULCC (Land Use and Land Cover Change): Direct or indirect human modification of the earth's terrestrial surface. Land cover refers to the physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures. Land use refers to activities such as agriculture, forestry and building construction that alter land surface processes including biogeochemistry, hydrology and biodiversity.
- MAI (Mean Annual Increment): Equivalent to Maximum Sustainable Yield (MSY).

- MC (“Monte Carlo” simulation): a modeling technique in which the same model is run repeatedly while uncertain parameters are varied according to a given probability distribution.
- NRB (non-renewable biomass): Extraction of woody biomass at rates exceeding the rate of natural re-growth within a given time period, most commonly one year. Note, the spatial distribution of NRB may differ from that of fNRB because each has a different relationship with biomass productivity. Productivity is spatially heterogeneous so, if wood extraction in areas with low productivity exceeds sustainable supplies by a small quantity, it may result in high fNRB though overall NRB may be low. In areas of high productivity, the opposite may occur.
- Realization: Each of many homologous simulations (i.e. set under same parameters and assumptions) that are run to account for uncertainty and sensitivity. Realizations should be understood as the process of how simulations “come out” after each Monte Carlo run.
- r_{\max} (maximum growth rate: Equivalent to Maximum Current Increment (MCI).
- Simulation: A progression of fuelwood harvest-regrowth spatial patterns over a given time period in discrete time steps or iterations. In this case study, each simulation lasts 30 years, by annual time steps.
- tDM (tons of dry matter).
- TOF (trees outside forests): Trees on farmland, household compounds, and roadside commons, where people access wood by pruning live trees and/or collecting dead/downed branches. This category also includes shade trees in coffee plantations, which are pruned regularly and constitute a major source of wood in coffee-growing parts of the study region.

Introduction

This study examines woodfuel sustainability in Haiti and explores the implications of various near-term household energy pathways for the small island nation. Fuelwood and charcoal represent nearly 80% of the country’s primary energy supply (IEA 2015) and Haiti has long been considered an archetypal case of woodfuel-driven deforestation (Voltaire 1979; Stevenson 1989). Popular environmental media have perpetuated this narrative (Cobb 1987; Diamond 2005; Gronewold 2009; Auch 2014). 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 (FAO 2000; FAO 2005; FAO 2010). 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% (Churches, Wampler et al. 2014), and other analyses support these findings (Tarter 2016).

While these authors advocate a radical rethinking of how we view Haiti’s forest cover, they still stress that Haiti’s forest cover has been severely degraded. Demand for both charcoal and fuelwood is increasing, driven largely by rapid urbanization. The impacts of increasing demand remain uncertain, and may extend beyond Haiti’s borders. For example,

numerous reports note that large volumes of Haiti's charcoal originate from the Dominican Republic (ESMAP 2007; Kheel 2014), which has also experienced high rates of forest loss.

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 in neighboring DR. More detailed research could clarify where impacts of additional woodfuel demand are likely to be felt, and whether proposed interventions can effectively deflect 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 had two main objectives:

1. Develop a spatial database to quantify the fraction of non-renewable biomass (fNRB) harvesting linked to woodfuel demand and identify "high risk areas" where sustainability of biomass resources is a major concern.
2. Develop a series of nine scenarios including a business as usual (BAU) scenario, examining the potential impacts of Haiti's future charcoal demand. The scenarios will explore how eight sets of interventions focused on demand reduction will affect fNRB throughout the country.

Background

Historical Patterns of Deforestation in Haiti

The ongoing drivers of deforestation in the island nation of Haiti have evolved over five centuries. The colonial powers of the late seventeenth and 18th century engendered a vast modification of the Haitian landscape through the implementation of a plantation model of intensive agricultural production, made possible through the forced labor of hundreds of thousands of enslaved people from West and Central Africa (Lindskog 1998; Moya Pons 2007; Tarter, Kennedy Freeman et al. 2016). Plantation-based agricultural production of the colonial period was accompanied by the clearance of fine tropical hardwoods from lowland alluvial plains, which were exported to France and elsewhere. Trees were also felled in nearby mountains to meet the lumber needs of the growing colony, the intense fuel demands of hundreds of sugar refineries, and later during a shift from the initial colonial crop suite toward coffee production in nearby mountains (Catanese 1999).

After a lengthy revolutionary period that culminated in independence in 1804, deforestation in Haiti was driven by two primary forces: (1) a negotiated war indemnity with France, funded through vast timber concessions to private, foreign entities; and (2) settlement by hundreds-of-thousands of Haitian families as they fanned out across the countryside to establish smallholder farms as an alternative to the colonial-era plantation model that early revolutionary leaders sought to perpetuate (Bulmer-Thomas 2012; Tarter 2015a).

In the early 20th century, U.S. Marines occupied Haiti (1919-1934), working to improve the country's infrastructure (Leyburn 1998 [1941]). Bridges and roads opened previously isolated parts of the country (Tarter, Kennedy Freeman et al. 2016). Toward the close of

WWII, the U.S. Department of State commissioned a report on the state of Haiti's forests, noting "forests in Haiti of commercial importance are practically non-existent" (Klein 1945). By the middle of the 20th century, most of the original forests of Haiti were gone.

The Role of Charcoal Production

The vast new network of roads and bridges created by U.S. Marines accelerated urban migration (White 1994). While rural Haitians traditionally cooked with firewood, the swelling urban population increasing relied on charcoal—a much lighter fuel that could be easily transported to the capital from remote locations. However, references to charcoal fail to appear in the literature until the 1930s (Tarter 2015a). Thus, while it is plausible that some remaining forests succumbed to charcoal production in the post-war period, clearing for agricultural production is considered the dominant driver of past deforestation in Haiti.

Charcoal for Port-au-Prince was initially procured from dry forests or arboreal fallow in areas peripheral to the city. However, over time, fallows were shortened or eliminated altogether in areas near the capital (Murray 1977). Eventually over-exhaustion of Haiti's traditional woodlot systems saw charcoal production shift from east of Port-au-Prince toward the island of La Gonâve, then the northwestern peninsula, and later to the southern peninsula and central plateau (Conway 1979; Voltaire 1979; Smucker 1981; Tarter 2016). One assessment suggests that by 1980, only 5% of charcoal consumed in Port-au-Prince came from the area east of the capital, while an additional 5% came from central Haiti; 10% from La Gônave; 50% from the northwestern peninsula; and 30% from the southern peninsula (Voltaire 1979).

During this era, many analyses concluded that woodfuel-dependent countries were in "crisis" (Eckholm 1975; de Montalembert and Clement 1983) and Haiti was not immune. Voltaire predicted charcoal production would shift from the rapidly depleting areas of La Gônave and the northwest, to the central plateau and the southern peninsula where wood supplies would meet demand until the year 2000, but eventually face environmental "apocalypse" (Voltaire 1979). These forecasts were supported by remote sensing analyses of aerial photographs from 1956 to 1978 (Cohen 1984).

Current State of Forests in Haiti

Despite the loss of much of the country's original forest cover, Haitians continue to meet their wood and charcoal demand. The earliest comprehensive survey of charcoal production in Haiti was administered in the mid-80s, and estimated that the Northwestern area of Haiti was supplying 34% of charcoal consumed in the capital; La Gônave supplied 7%; the central plateau area supplied 13%; the Southeast supplied 10%; and the southern peninsula 36% (Grosenick and McGowan 1986). Thus, Voltaire's predictions about the geographic shift in charcoal production held true; however, the "apocalypse" has yet to materialize.

More recent analyses of La Gônave shows that between 1990 and 2010, the island experienced a 23% loss of forest and/or dense vegetation cover, but an 87% increase in woody shrubland during the same time period. In addition, land that was classified as

“Barren/Eroded’ declined by 7%, with the majority reverting to shrubland and forest (White, Shao et al. 2013).¹

A similar study used Landsat images from Haiti’s dry season in 2010-2011 to estimate country-wide forest cover. The authors reclassified Landsat data using FAO’s forest class definition to define low and high ranges of tree-cover. Classifications were verified through a stratified sample of 1,525 random reference points using higher resolution imagery (Churches, Wampler et al. 2014). They found that 2010-2011, tree cover was 29-32% of Haiti’s land surface, ‘shrub/herbaceous’ areas covered 46-49 %. They also note that rather than existing in a thinly dispersed covering, trees are aggregated in fragments and patches (Churches, Wampler et al. 2014). A broader study of the Greater Antilles² between 2001 and 2010 found that Haiti experienced a 1% in woody vegetation cover and 4% increase in mixed-woody/plantation cover (Álvarez-Berríos, Redo et al. 2013).

These recent studies indicate that Haiti’s tree cover is more extensive than previously imagined, and not necessarily on a downward trajectory. Not only have Haitians avoided environmental apocalypse, but in many locations, they have developed systems for sustainable woodlot management (Tarter 2015a), often managed in collective *eritaj* (kinship based) systems (Murray 1980a; Álvarez and Murray 1981; Lowenthal 1987; Tarter 2015b).

Contemporary Tree Use in Haiti

Haitians rely on trees for many things in addition to fuelwood and charcoal: boundary markers; live fences; fruit and forage; construction; medicine; soil conservation; tools and furniture; shade for animals and coffee; (Mintz 1962; Conway 1979; Smucker 1981; Balzano 1986; White 1994; Tarter 2010). Haitians also have strictures against cutting certain trees for religious or spiritual reasons (Tarter 2015b).

Trees represent an important source of income for rural Haitians and charcoal is one of the most important tree-based products. Primary education is nearly universal in rural Haiti and school costs are a periodic expense that all families face. Charcoal is produced year round, but production swells before the beginning of each school semester, when school fees are due. Charcoal is also produced during periods of drought, when crop failure is widespread.

Haitian Charcoal Production Systems

Estimates of the national energy need met by charcoal or firewood in Haiti range from 66-85% (Howard 1998; Van der Plas 2007) and over 80% of charcoal produced in Haiti is consumed in the capital of Port-au-Prince (Van der Plas 2007).

¹ The study relied on Landsat satellite images from 1990 and 2010. Images were from late January, Haiti’s dry season, which controlled for seasonal variability in vegetation and cloud cover.

² A group of Caribbean island states including Cuba, Haiti, the Dominican Republic, Puerto Rico, Jamaica, and the Cayman Islands.

Haiti's charcoal is produced primarily in *rakbwa* (woodlot) systems that are common throughout the countryside. *Rakbwa* commonly contain small, young trees, or coppice from larger tree stumps 1-7 meters tall, with densities from ranging from impenetrable thickets to easily traversed open woodlots. Heavily managed plots tend to be more dense, with one plot occasionally adjoining another, creating areas that can only be traversed by a series of preexisting, machete-hacked footpaths. *Rakbwa* are managed on a coppice cycle of 3-7 years with a combination of active and passive measures. When managed correctly, farmers report that *rakbwa* can be coppiced indefinitely (Tarter 2015a). Pasiiecznik et al. noted *Prosopis juliflora*, the most common species in *rakbwa* systems, can "coppice very well, resprouting rapidly following hard and repeated cutting without showing any detrimental effects," (Pasiiecznik, Felker et al. 2001, p. 4). Commonly suggested techniques for cultivating wood coppice include thinning of trees and removal of excess coppice, clearing of understory, and cutting trees high enough to protect new coppice from animals (Pasiiecznik, Felker et al. 2001). However, Haitian farmers rarely thin or remove understory, because doing so provides little improvement to the system and requires an unjustifiable exertion of time and energy.

Rakbwa trees vary in diameter from the size of a common broomstick to a wooden fence post, but rarely reach larger sizes. The majority tends to contain smaller trees and there is little variation in age and size within a given woodlot. The diversity of plant species is also quite low, with *rakbwa* are predominantly populated by just two species: *bayawonn* (*Prosopis juliflora* (Sw.) DC.) and *kanpèch* (*Haematoxylon campechianum*) (Tarter 2015a). Both are exotic and potentially invasive species that were naturalized in Haiti during the colonial era (Hatzenberger 2000).

The current extent of coverage by these two species is unknown. However, previous estimates indicated that *Prosopis* alone constituted the dominant species in all types of woodlands, covering approximately 300,000 hectares in the early 1990s.

Methods

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 platform bundles together several freely available software packages and has been described in detail elsewhere (Ghilardi, Bailis et al. 2016). Hence, we do not provide a detailed description here. However, some aspects were adapted to accommodate unique dimensions of Haiti's woodfuel supply and demand: we review these below. Appendix A lists all inputs used in this analysis.

One common practice in environmental modeling to test for model's outcomes validity is to run simulations that begin in the past and ending in the near future. This allows for comparison of mid-point results of the simulations to present day data. However, simulations often predict small changes in land cover or aboveground biomass stock that do not appear in available low- to medium-resolution satellite imagery. These require costly field work or very high resolution imagery to validate (e.g. Asner, Powell et al. 2010).

Definitions of model's key output parameters

We assume the growth of above ground (woody) biomass (AGB) is a function of three factors: the stock remaining after the previous iteration, the maximum growth rate (r_{\max} : the first derivative of a logistic "S-type" curve), and the maximum biomass density or "carrying capacity" (K) (Ghilardi, Bailis et al. 2016). Both r_{\max} and K depend on biophysical parameters such as land cover, soil, hydrology, insolation, and altitude. However, data for multiple biophysical growth parameters is rarely available. In this case study, we define K and r_{\max} based solely on LULC class. Equation 1 describes this relationship:

$$AGB_{(t+1)i} = AGB_{(t)i} + AGB_{(t)i} \cdot r_{\max} \cdot \left(1 - \frac{AGB_{(t)i}}{K_i}\right) \quad (\text{eq.1})$$

$AGB_{(t)i}$ and $AGB_{(t+1)i}$ are above ground woody biomass suitable for fuelwood in LULC class "i", at time "t" and "t+1" respectively. Appendix B lists the relevant parameters for each LULC class.

Non-renewable biomass (NRB) is the amount of harvested wood that exceeds natural re-growth over a given time period. The ratio of NRB to total woodfuel consumption indicates the "fraction of non-renewable biomass" (fNRB): the proportion of the wood harvest that is unsustainable.

The model iterates a series of time steps (one year in this study), with n-steps per simulation. MoFuSS can run for any simulation length (24 years in this study) and produce three primary outputs for each time step "t": a) AGB_t , b) NRB_t defined only in the pixels where decreases in AGB have occurred (equation 2), and c) $fNRB_t$, also defined in pixels where decreases in AGB have occurred. For each pixel:

$$NRB_{(t=n)} = \begin{cases} AGB_{(t=0)} - AGB_{(t=n)} & \text{if } AGB_{(t=0)} > AGB_{(t=n)} \\ 0 & \text{if } AGB_{(t=0)} \leq AGB_{(t=n)} \end{cases} \quad (\text{eq.2})$$

Where $NRB_{(t=n)}$ is the amount of fuelwood in tDM which, when harvested, results in a net decrease in AGB between time $t=0$ and $t=n$. In this assessment, n can consist of one or many single-step iterations; $n = 24$ corresponds to the entire simulation. Each MC run generates a different value of $NRB_{(t=n)}$ by repeating equation 2 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 $AGB_{(t=n)} \geq AGB_{(t=0)}$. In other words, $NRB_{(t=n)}$ is not the net decrease of AGB over the entire "fuelwood-shed". Instead, it accounts for losses of AGB only in the set of pixels where a loss occurred.

fNRB is calculated as:

$$fNRB_{(t=n)} = \frac{NRB_{(t=n)}}{C_{(t=n)}} \quad (\text{eq.3})$$

where C is total residential fuelwood consumption in tDM for any time step "t". C can be expressed as $C_{(t=n)}$, corresponding to the summed fuelwood consumption between time 0

and time n . As C is loaded at each single-step iteration, temporal (and spatial) changes in fuelwood use, which may be induced by a gradual and spatially uneven diffusion of ICS, can be simulated.

Demand

Household woodfuel demand was produced by assigning fractions of different types of cooking fuels available at 2nd administrative level (Institute Haïtien de Statistique et d'Informatique République d'Haïti 2003) to a 2003 gridded map of population distribution (Derek Azar, Jordan Graesser et al. 2010). Figure 1 shows gridded distribution of population using diverse types of household fuels, either alone or in combination. Per capita consumption of fuelwood and charcoal from (ESMAP 2007) were assigned to population maps in order to obtain a gridded map of combined fuelwood and charcoal demand in year 2003 (Figure 2).

Per capita consumption of charcoal and fuelwood reported in the ESMAP study was 0.46 and 1.50 kg/person-day respectively. Both were multiplied by the average household size in 2003 (4.9 people) to obtain demand per household. 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 (Bailis 2009).

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 (Institute Haïtien de Statistique et d'Informatique République d'Haïti 2003). For these households, we assumed consumption of either charcoal or fuelwood was half that of households using those fuels alone.³

³ The 2003 census lacked data on households using charcoal with LPG; however, we assumed that it was ~6% of the population which matched a later dataset (CNIGS 2012).

Figure 1: Gridded population using woodfuels in 2003

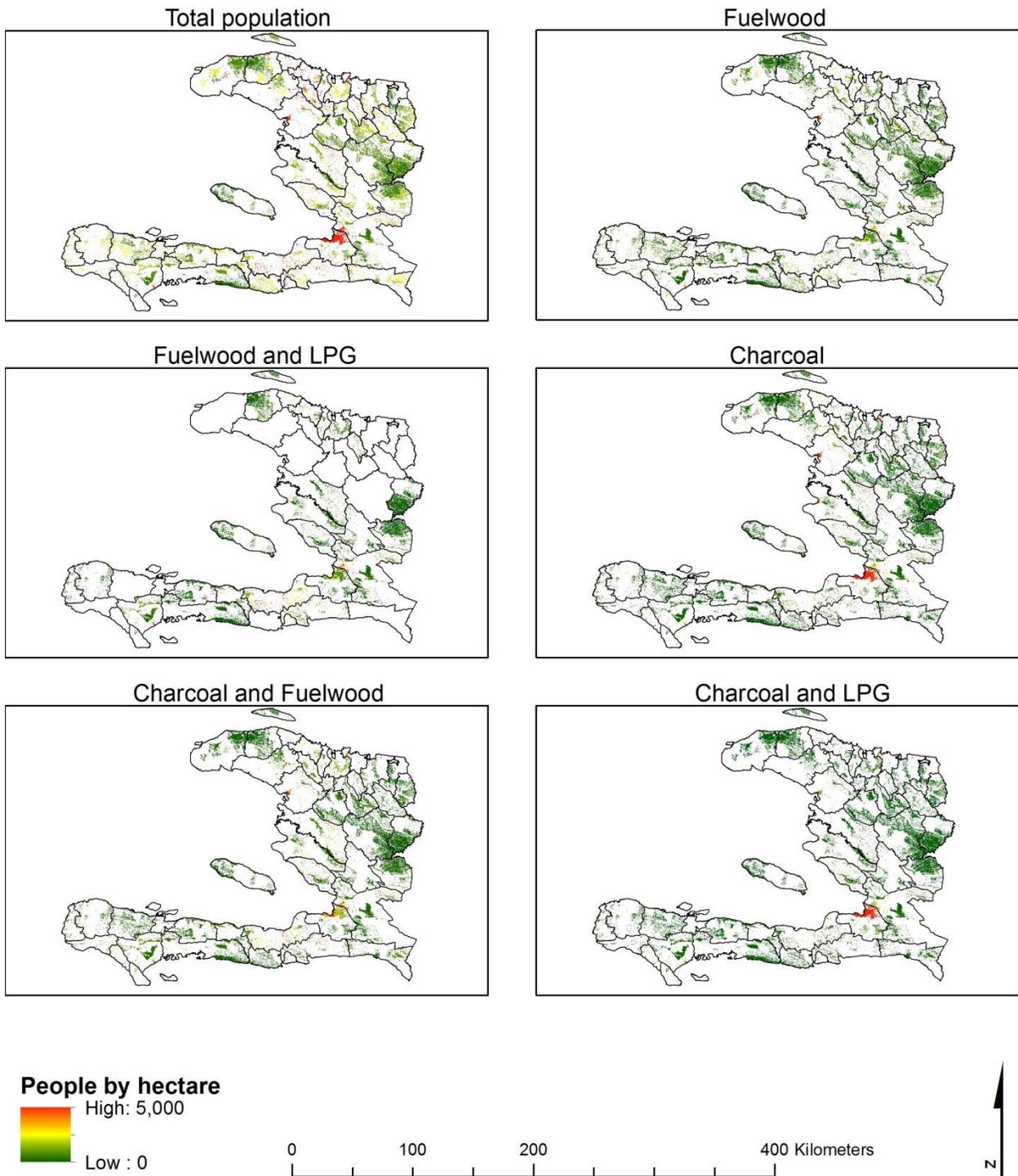
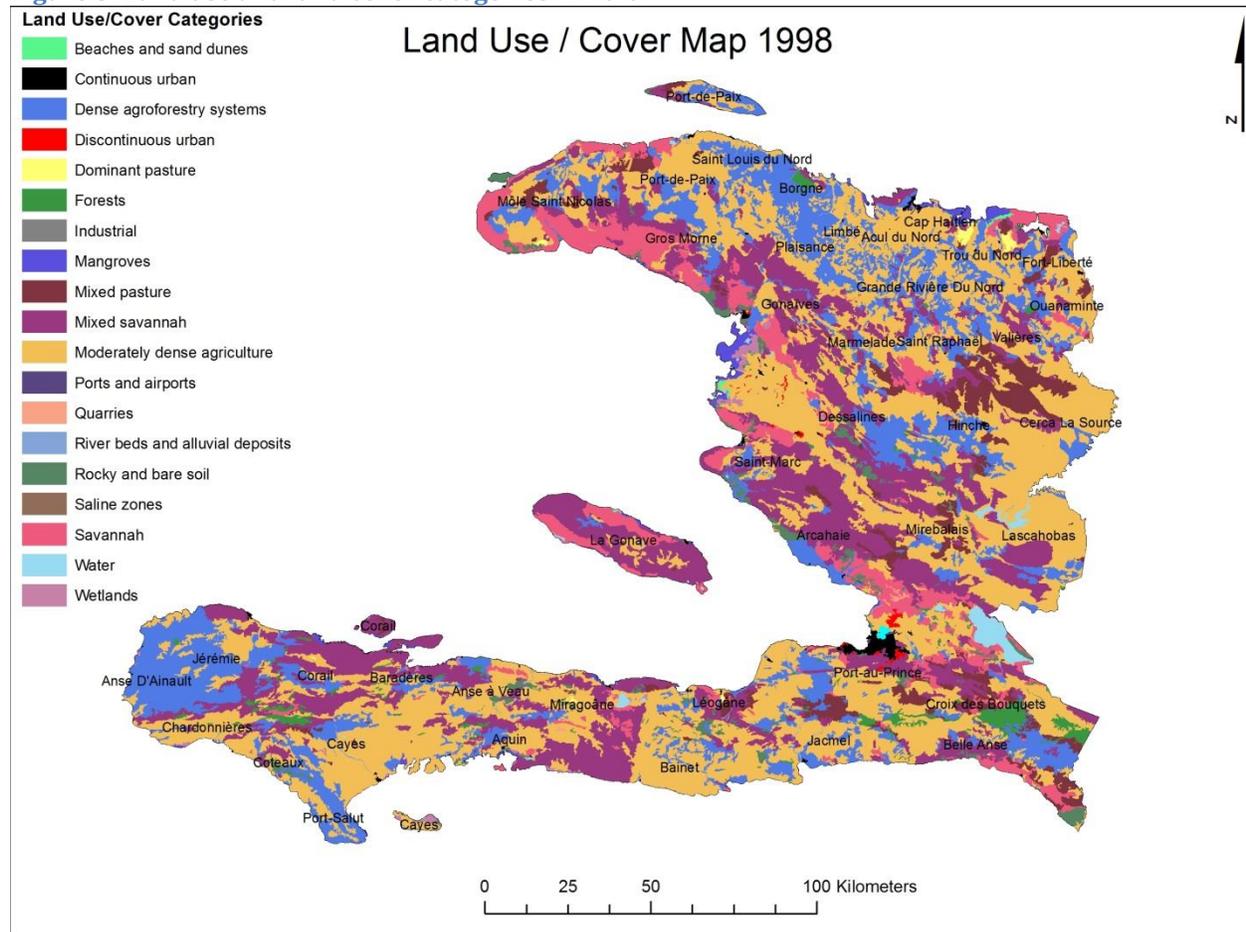


Figure 3: Land use and land cover categories in Haiti



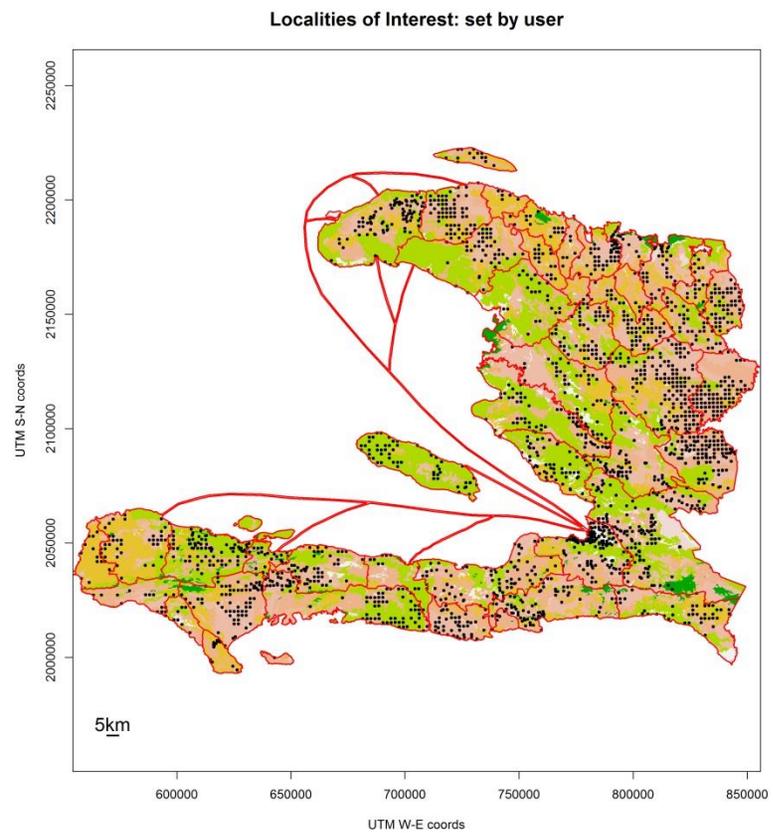
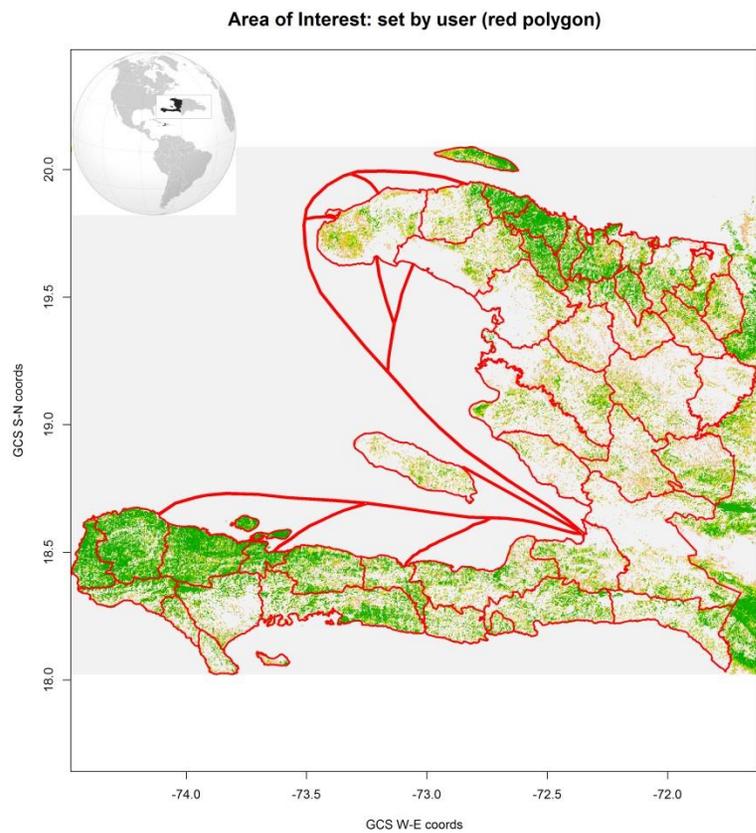
Integration of supply and demand

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 (Ghilardi, Bailis et al. 2016). All locations, whether harvested or not, can accumulate biomass (as described in eq. 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 4. Integrating potential woodfuel supply and demand results in a mapping of harvest pressure for both self-gathered and commercial demand (shown in Appendix C).

Dealing with uncertainty

A Monte Carlo module accommodates inherent uncertainties associated with input parameters.

Figure 4: Tree cover (%) in year 2000 and AGB (t/ha) circa 2003



Scenarios

Scenarios were developed in collaboration with the GACC Haiti team and divided into urban and rural interventions. Scenarios 1-4 focused on various transitions away from solid fuels in traditional cooking devices: each pathway moved either toward LPG and ethanol or maintained the use of solid fuels, but introduced more efficient stoves. In the urban interventions, the transitions occurred solely among charcoal users, while in rural areas, both fuelwood and charcoal users are affected. A fifth scenario maintained current fuel mixes, but incorporated more efficient charcoal conversion technology. The transitions are summarized in Table 1 below.

Table 1: Scenario characteristics

Names and descriptions	Codes and percentages			
	s0			
Business as Usual (BAU)	s1_a	s1_b	s1_d	s1_r
Urban (rural for s1r) with LPG, EtOH and improved charcoal stoves: between 2017 and 2027				
Charcoal users adopt LPG and/or ethanol	70%	50%	25%	70%
Charcoal users adopt an improved charcoal stove (eff = 43%)	20%	20%	50%	20%
No change	10%	30%	25%	10%
Rural with LPG, EtOH and improved charcoal stoves: between 2017 and 2027	s2_a	s2_c		
Charcoal and fuelwood users adopt LPG and/or ethanol	30%	10%		
Charcoal and fuelwood users adopt an improved charcoal stove (eff = 43%)	40%	60%		
No change	30%	30%		
Rural with LPG, EtOH and char-briquettes or pellets: between 2017 and 2027	s3			
Charcoal and fuelwood users adopt LPG and/or ethanol	30%			
Charcoal and fuelwood users adopt an improved stove using char-briquettes or pellets	40%			
No change	30%			
Rural with improved woodstoves	s4			
LPG	10%			
Improved woodstoves	60%			
No Change	30%			
Improved charcoal kilns: between 2017 and 2027	s5			
Charcoal production is carried out in improved kilns	50%			

We make the following assumptions for each scenario:

- The scenarios cover 2003 - 2027 and are presented as gridded data disaggregated to the 3rd administrative level (570 communes).
- Population growth is the same under all scenarios and defined by UN population projections (see Appendix)
- 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

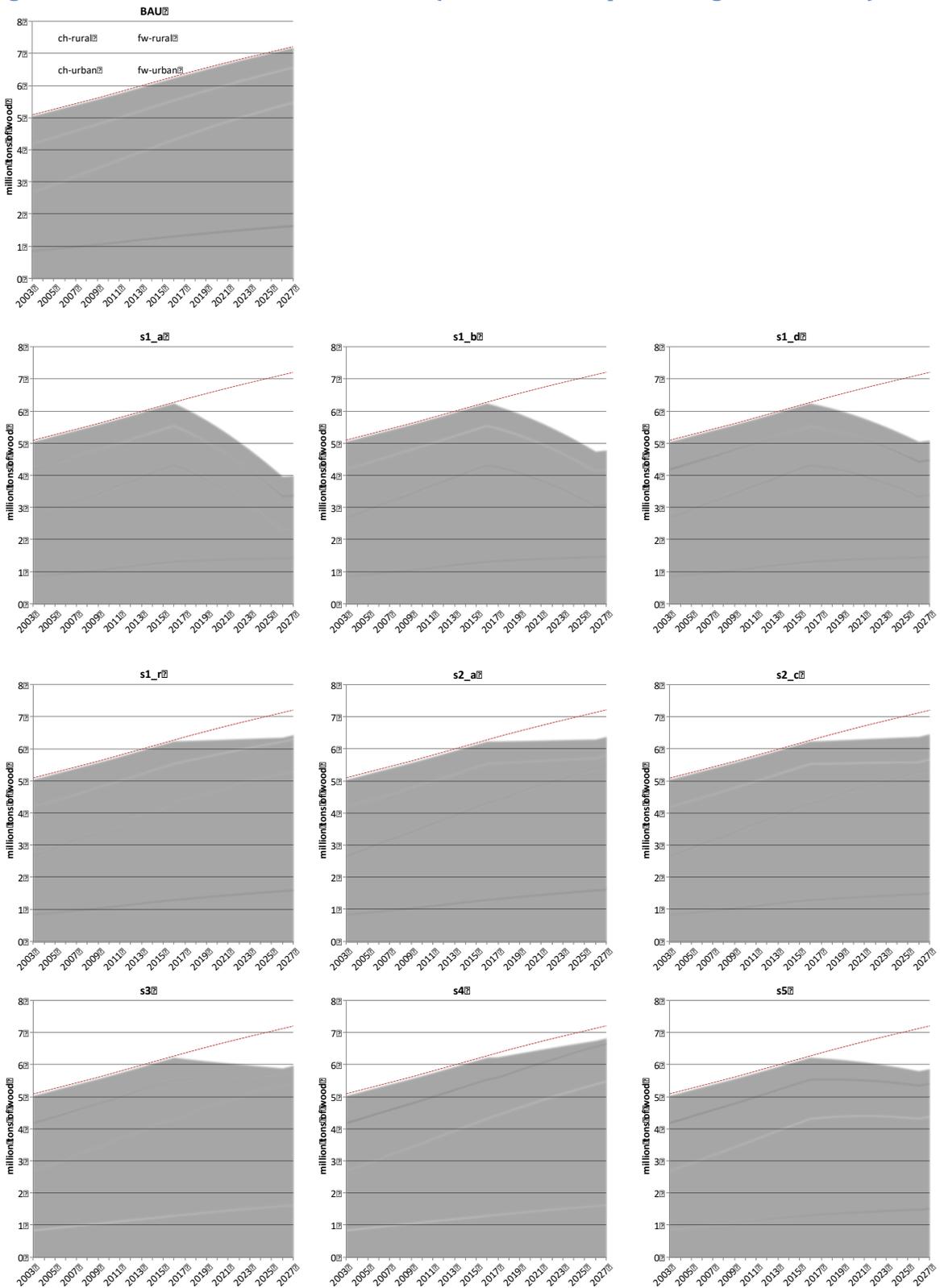
- Briquettes and pellets are derived entirely from agricultural waste and require no tree cutting. Therefore briquette production has no impact on land cover.
- Similarly, ethanol production has no impact on land cover.
- Improved charcoal double mass-based conversion efficiency (we assume traditional earthmound kilns are ~20% efficient and the retort kilns that are introduced are 40% efficient)⁴

The scenarios result in wood demand reductions ranging from 4% (s1c) to 60% (s1a). Demand trajectories are shown in Figure 5. 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.

Note several scenarios show an uptick in wood demand between 2026 and 2027 because the interventions are implemented over a 10-year period from 2017 to 2026. Thus the adoption of new technology ceases to grow in the final year of the simulation. Increased demand due to population growth is 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.

⁴ 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 (Bailis 2009).

Figure 5: Wood demand under each scenario (codes and assumptions are given in Table 1)



Results

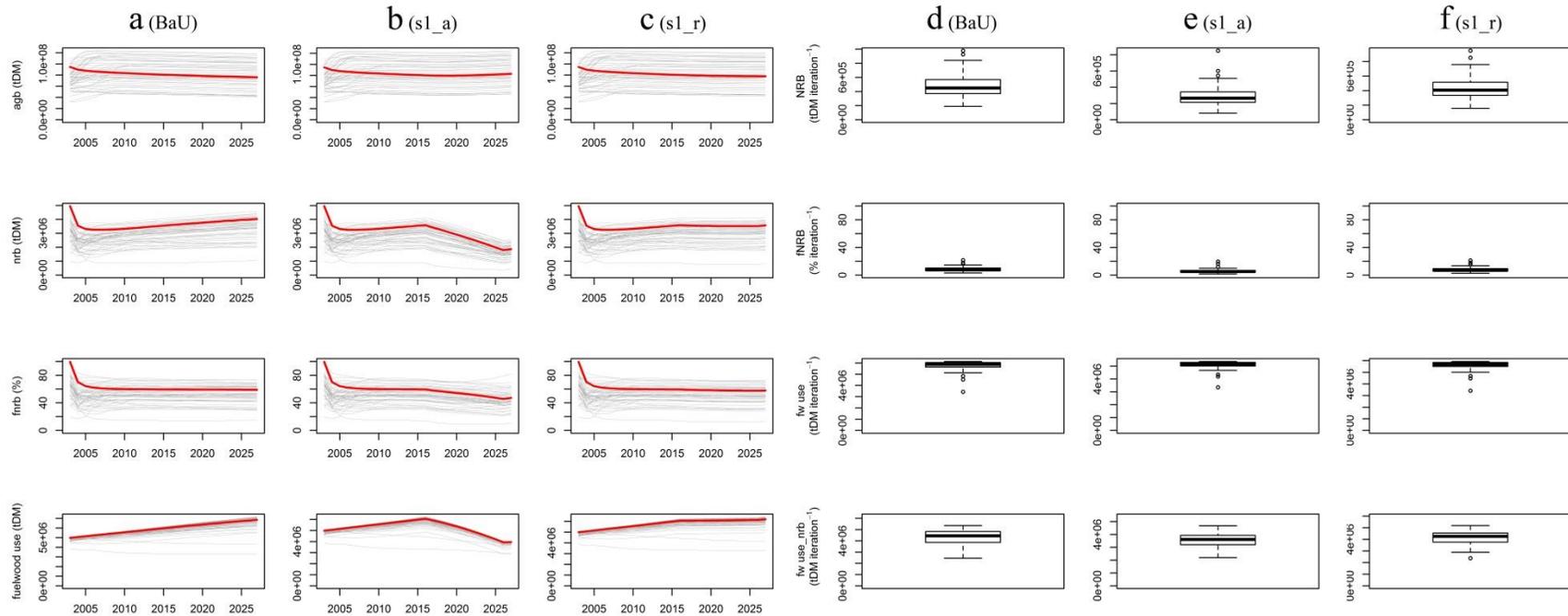
Figure 6 compares results from the BaU, s1a and s1r simulations. Bold red lines show the results that are calculated when mean values for key parameters are used; light gray lines show results for other realizations of the Monte Carlo simulation. This discussion focuses mainly on s1a because it is the most “extreme” intervention in terms of woodfuel demand reduction (see Table 1). Results of other scenarios are shown in Appendix D. 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 preliminary results indicate that under BaU conditions, woodfuel demand leads to the cumulative harvest of 13-19 million tons of non-renewable biomass over the simulation period, leading to a loss of 3-20% AGB. Overall demand for woodfuel during the simulation varies from 130-150 million tons, resulting in fNRB of $9 \pm 3\%$ (mean \pm standard deviation). Under scenario s1a, woodfuel demand drops by 44% by 2027. This leads to a 6-11% decrease in cumulative harvest over the entire simulation period and 41% reduction in cumulative NRB extraction.

Figure 7 and Figure 8 show maps of AGB, NRB and fNRB from each scenario. Figure 9 and Figure 10 show more detailed views of NRB and fNRB for BaU with administrative unit highlighted. Under the BAU scenario, the largest NRB extraction occurs in the arrondissements close to the capital (Croix-Des-Bouquets and Arcahaie to the north and rural parts of Port-au-Prince to the south). Due to their proximity to the main center of demand, the model predicts that these regions will experience a higher volume of unsustainable woodfuel extraction than other regions of the country. There are also notable concentrations of NRB extraction in arrondissements north of Port-au-Prince Gonaives, Dessaline, and Saint-Marc as well as arrondissements in the Southern Peninsula like Miragoane and Aquin. With s1a, NRB impacts still occur in these regions, but they are substantially diminished.

Like s1a, scenarios s1b and s1d also focus on urban areas, but involve more modest interventions and are likely to lead to lower reductions in NRB. Scenarios s2, s3, and s4 focus on demand in rural areas, where fuelwood is more prevalent than charcoal. These should also result in smaller improvements relative to s1a, because rural demand for woodfuels is smaller than urban demand, and is more dispersed across the landscape. Scenario s5 focuses equally on rural and urban regions by making charcoal conversion more efficient and reducing overall demand for wood extraction. However, due to large uncertainties in key parameters, key outcomes like NRB reduction relative to BAU show considerable overlap. Detailed results from each scenario are shown Appendix D.

Figure 6: Behavior of AGB, NRB, fNRB and total fuelwood use between BaU, s1_a, and s1_r. Plots a-c show the annual progression of outcomes and d-f show the outcome at the end of each simulation.



Note: Red lines were generated using mean user-defined parameters shown in Appendix B, while light grey lines were generated in each MC realization using varying parameters (50 MC realizations in this case). fNRB is calculated as the fraction between NRB and total woodfuel consumption. Box-and-whisker plots show the median of the MC distribution as a dark line, inter-quartile range (IQR) by the top and bottom of the box, and min/max of the range by the whiskers. Some plots have outliers, defined as data points between 1.5 and 3 IQR's from either end of the box, shown by small circles.

Figure 7: Spatial behavior of AGB between 2003 and 2027 in the BaU and s1_a scenarios

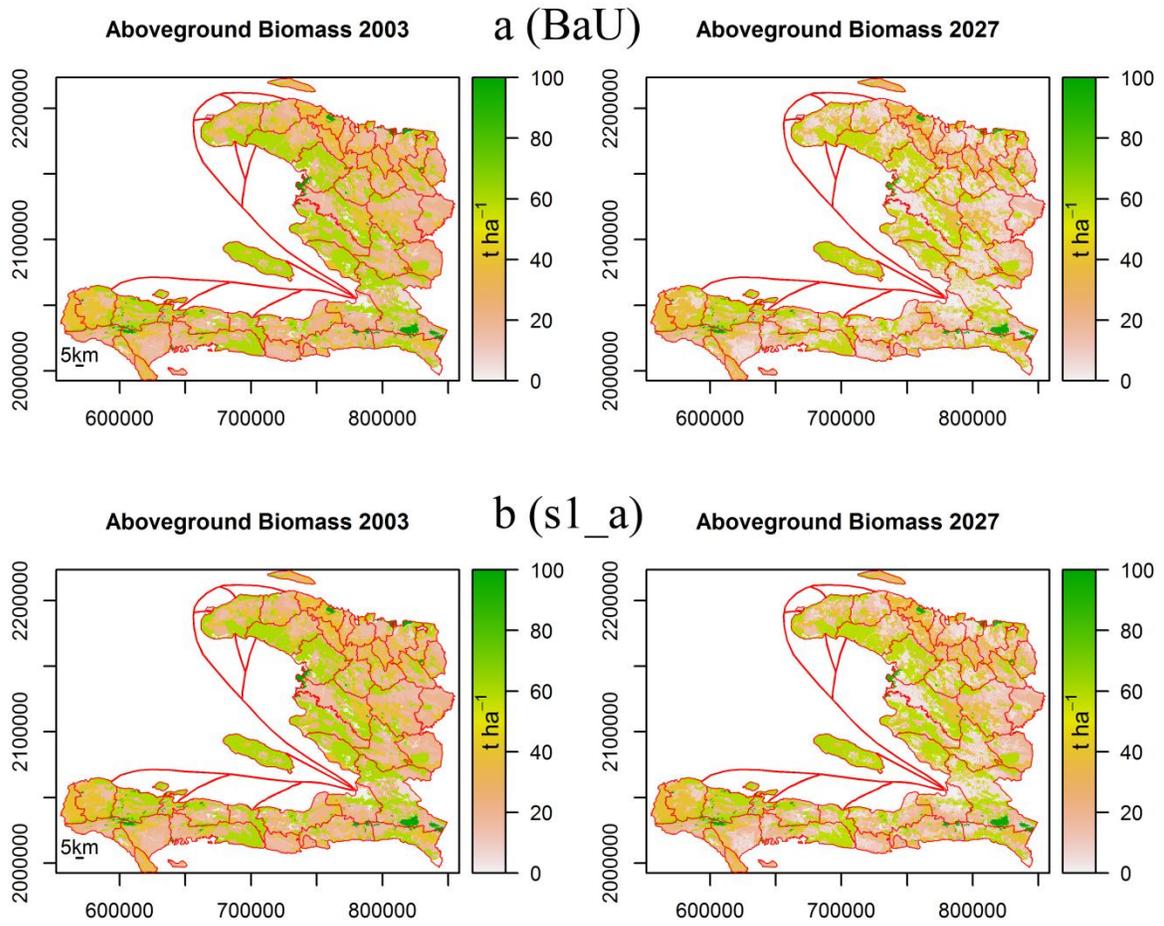


Figure 8: Cumulative NRB extraction (left) and overall fNRB (right) in BaU (top) and s1_a (bottom)

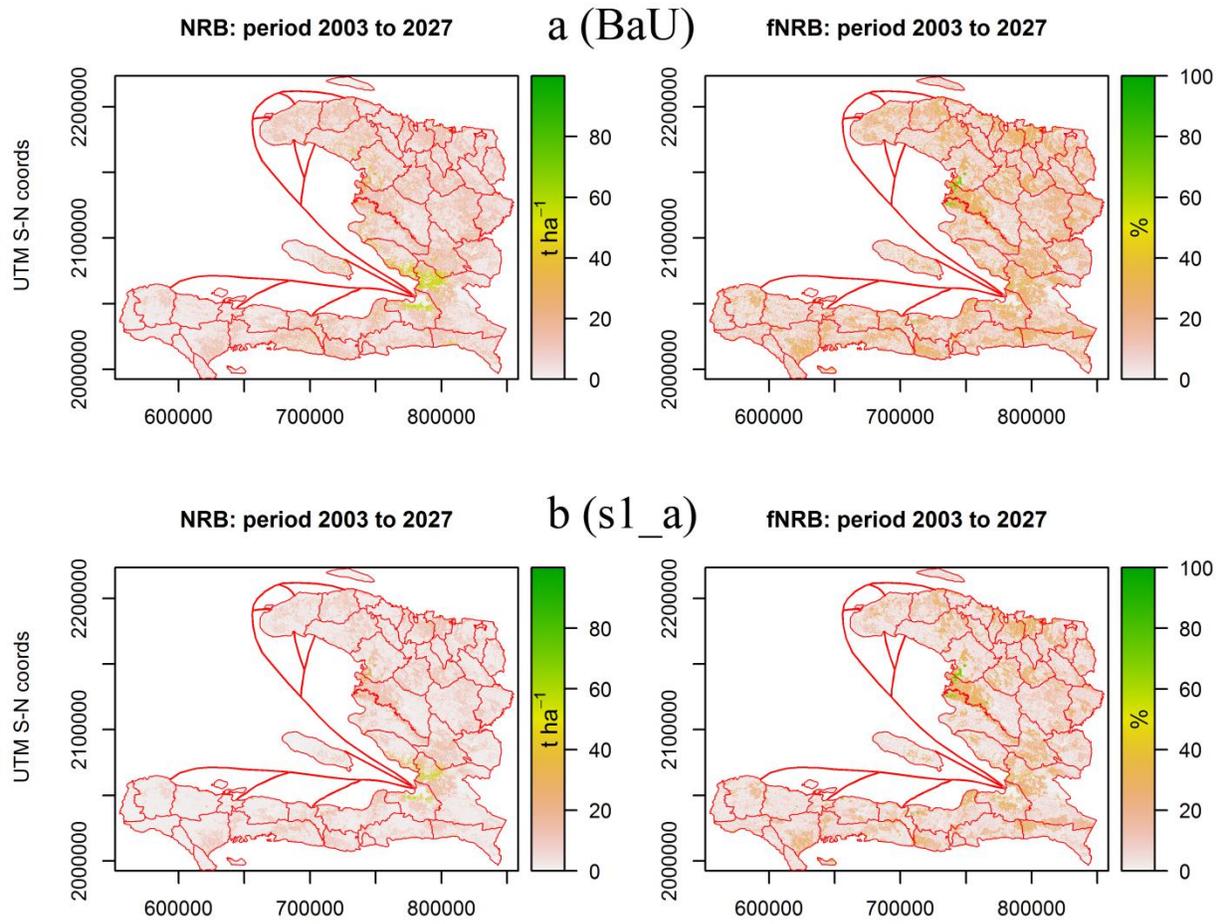
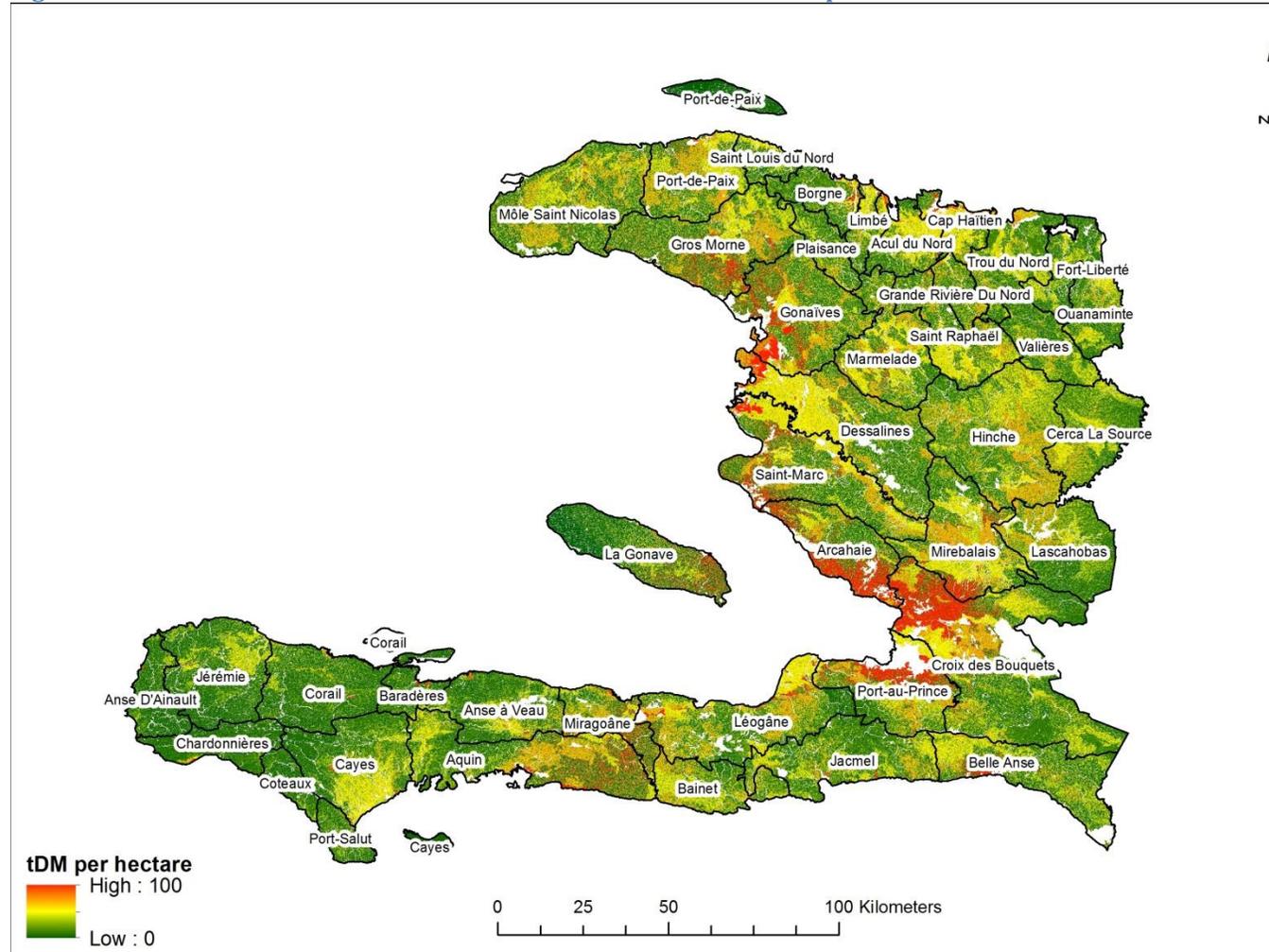
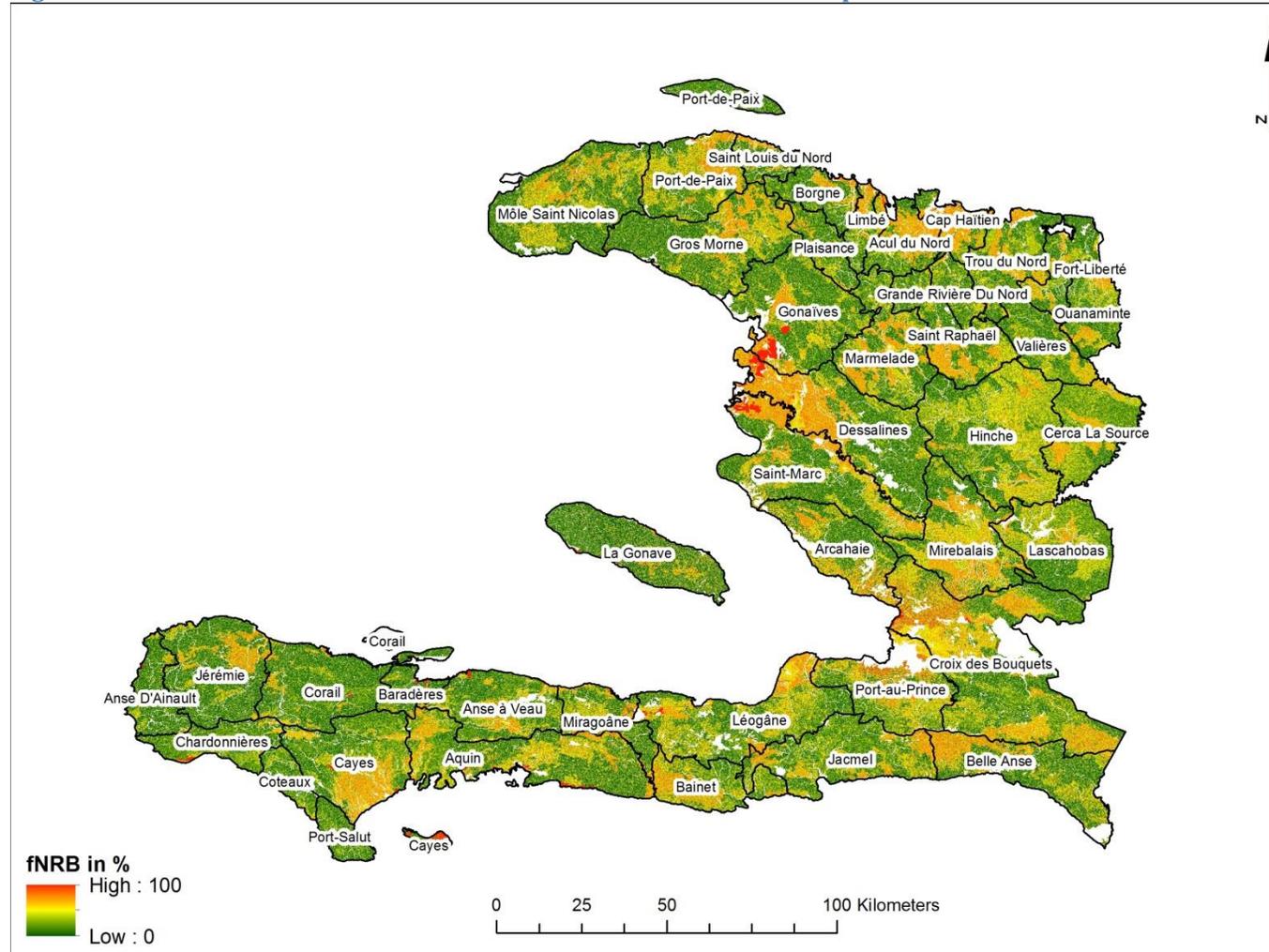


Figure 9: Cumulative NRB in the BaU scenario for the entire simulation period 2003-2027



Notes: The map shows the first Monte Carlo realization only. Note this map is the same as Figure 8 (a - left).

Figure 10: Cumulative fNRB in the BaU scenario for the entire simulation period 2003-2027



Notes: The map shows the first Monte Carlo realization only. Note this map is the same as Figure 8 (a - right).

Conclusions/Next steps

Results show that under a business-as-usual (BAU) scenario, existing woody biomass resources are insufficient to fully satisfy Haiti's current and future demand for wood energy without some loss of standing biomass. Our simulations show that these impacts would be lessened if interventions to reduce woodfuel demand were successfully implemented over the next decade. Under the most aggressive scenarios, the loss of standing biomass could be fully arrested, and stocks could potentially recover. However, the current results are still too uncertain to guide policy measures or interventions. We propose several steps including consultations with additional experts within Haiti and a campaign of targeted fieldwork to reduce uncertainty of several critical parameters, while validating some of the results by comparing simulated vs observed data at present time.

Future Research Directions

- The first step will be to conduct a sensitivity analysis to better understand the effect of each parameter in model results. 107 parameters are used for the current simulations, past experiences indicate that the model is most sensitive to between 10 and 20. These will form the focus of more rigorous sensitivity analyses.
- Specifically, previous experience tells us key parameters that likely need to be refined are associated with woodfuel availability and productivity. For example:
 - Including ecozones to improve maps of wood for charcoal productivity (e.g. revising "Holdridge life zones" for Haiti, incorporating other climatic zones, insolation, Topographic Wetness Index (TWI), etc.).
 - Separating dense and mid-dense cropland into classes hosting varying amounts of trees usable for charcoal and fuelwood.
 - Improving parameterization of trees outside forests.
 - Improving land cover mapping by classifying at least three dates (for validation purposes) with an increased resolution (not less than 100 m).
 - Improving our understanding of coppicing systems for charcoal production across the country, in order to separate assumptions on wood regrowth by other spatial variables apart from land use/cover.
- Although a simple version of charcoal imports from the Dominican Republic was coded into the model, no simulations were produced because to the lack of any information about the transported volume. Currently, the model will assume that all imports from the Dominican Republic will be used in Port-au-Prince, but neither a porous border nor transport routes have yet been coded. It is worth mentioning that a newly approved project by CEPAL, and coordinated by the authors of this report, will focus on Dominican Republic dendroenergy potential, including a spatial and temporal analysis of illegal charcoal exports into Haiti.

- Verifying results with empirical field-based data is a highly challenging but necessary task. One way to move forward is to use remote sensing techniques for quantifying forest degradation over areas and time spans forecast by the model, in places where degradation driven by woodfuel extraction should be significant. The task has to cope with multiple complexities, such as separating overlapping drivers to prove causality in any observed changes.

Other few minor improvements include:

- Refine/update boat routes and better account for boat size and speed.
- Confirm whether recent deforestation events (identified by Hansen, Potapov et al. 2013) are associated with charcoal production within coppiced woodlot systems.
- Revise village distribution mapping because some shifting might have occurred since the original maps were produced.
- Incorporate the impacts of population shifts and forests damage resulting from natural hazards like the 2010 earthquake and/or recent hurricane.
- In addition to woodfuels used residential purposes, include other uses such as charcoal or fuelwood for small industries.

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Appendix A

Table 2: Data used in analyses

	Input dataset	Type of data†	Description and source of data	
Spatial Data	1	Digital Elevation Model	raster	Data Elevation Model (DEM) at 30 meter created by the NATHAT mission in June 2010. Available at http://www.haitidata.org
	2	Tree cover 2000	raster	30 meter tree cover map. Available at: http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.1.html .
	3	Forest loss (annual) 2000-2013	raster	30 meter forest loss map (annual loss events between 2000 and 2013). Available at: http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.1.html .
	4	Forest gain (whole period) 2000-2012	raster	30 meter forest gain map (gain events for the period 2000-2012). Available at: http://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.1.html .
	5	Land Use/Cover Map 1998	vector	The map is drawn at a 1:300,000 scale. It was created by the Haitian National Centre for Geospatial Information (CNIGS) in September, 2008, from cartographic maps and SPOT image, 1998. Available at http://www.haitidata.org
	6	Gridded population estimates 2003	raster	These population estimates are based on 2003 Haitian census data and methodology developed by the U.S. Census Bureau that uses census data and remotely sensed imagery to estimate population at a resolution of 100 meters. Available at http://www.census.gov/population/international/data/mapping/demobase.html
	7	Populated places	vector	Populated places of Haiti extracted from the OpenStreetMap (OSM) database. Available for 2US\$ at http://data.geocomm.com/catalog/HA/group140.html
	8	Road network	vector	Roads network, taken at a 1:50,000 scale. It was created by the Haitian National Centre for Geospatial Information (CNIGS) in September, 2006, from cartographic maps, 1956, with partial update in 2006. Available at http://www.haitidata.org
	9	Rivers	vector	River network in Haiti, at 1:50 000. It was created by the National Center of Geo-Spatial Information (CNIGS) in June 2006, from cards 1956. Available at http://www.haitidata.org

		Input dataset	Type of data†	Description and source of data
	10	Sea routes	vector	Created for the purpose of this study based on: http://www.hrdf.org/files/Substitution-of-Wood-Charcoal-by-Conversion-of-Cellulose-Products.pdf
	11	Administrative Units	vector	4th administrative level (Sections). Available at http://www.census.gov/population/international/data/mapping/demobase.html
Non-Spatial Data	15	Cooking fuel by 2 nd admin unit	database	Available at https://international.ipums.org/international-action/variables/group .
	16	Fuelwood and charcoal unitary consumption	single values	ESMAP 2007 data cited in: http://haitireconstruction.ning.com/page/charcoal-and-firewood

Appendix B

Literature review on woody biomass resources productivity

Woody biomass productivity is a major input in the model. It affects the sustainable supply of a given parcel of land as well as the rate of post-harvest regeneration. There is very little data available indicating the productivity of woody biomass at a landscape level in Haiti. However, many sources indicate that the majority of the country's woodfuel is derived from *Prosopis juliflora*, which occurs both in managed woodlots and in naturally occurring stands. The dominance of *Prosopis* allows us to approximate biomass productivity in difference LULC systems by using productivity data for *Prosopis* growing in other regions. In this section, we provide some background information about how *Prosopis* became the dominant tree cover and woodfuel feedstock in Haiti review the literature on its productivity.

The first known reference to charcoal in Haiti comes from 1924, when a geographer doing a nationwide survey noted that 'bayahonde [*Prosopis juliflora*] is used a great deal for fuel, some of it as charcoal', and 'most of the wood used in Port-au-Prince is that of the leguminous tree called bayahonde [*Prosopis juliflora*]' (Woodring, Brown et al. 1924, pp. 63 and 485, brackets added by authors). This is supported by a subsequent study from 1931, which reported that "as much bayahonde [*Prosopis*] is used for charcoal as all other species combined", (Gill 1931, p. 138, brackets added by authors). Other analyses from that era noted that *Prosopis* was the common along the border with DR (Palmer 1976), and it also appeared in dense stands on the offshore island of La Gonave (Wetmore and Swales 1931). By the mid-1940s, local charcoal-makers were heavily utilizing *Prosopis* in coppice systems. One study carried out 80 transects in thorn-woodlands and found high densities and frequencies of thin (1-3 inch DBH) sprouts from coppiced stumps (Curtis 1947).

Other authors note that *Lignum vitae* (*gayak* in Haitian Creole) was historically preferred for charcoal (Conway 1979; Voltaire 1979; Murray 1980b; Smucker 1981). However, *Gayak* grows very slowly, which may explain why it was not included in the managed woodlot systems that emerged during the 20th century. Conway (1979) noted charcoal producers pulled up long-dead *Gayak* tree trunks. The shift from *Gayak* to *Prosopis* for charcoal occurred gradually. One report notes that east of Pòtoprens, "the favorite trees for making charcoal locally are the *gayak* and the *Prosopis juliflora* trees" (Alvarez and Murray 1981) and a World Bank project proposal from the same era noted that in "many areas" both species are "subject to overcutting and are in regression", but that *Prosopis* is the primary feedstock because *gayak* had "largely disappeared" (World Bank 1982, pp. 5, 9).

These observations hold true for many of the contemporary areas of ongoing, intensive charcoal production in Haiti. Unfortunately the mangroves aren't as resilient, and many of the original dry forest tree species have been replaced principally by *Prosopis*, and to a lesser degree by functionally similar species, such as *Haematoxylon campechianum*.

Table 3: Wood productivity per class

Land Use/Cover Category	r _{max}	r _{max} SD	K	KSD	TOF
	% of AGB stock	% of AGB stock	tDM/yr/ha	tDM/yr/ha	Yes/No
Continuous urban	0	0	0.2	0.2	Yes
Discontinuous urban	0	0	0.1	0.1	Yes
Industrial	0	0	0.5	0.5	Yes
Ports and airports	0	0	0.1	0.1	Yes
Dense agriculture	0.5	0.1	15	5	No
Dense agroforestry systems	1	0.1	40	20	No
Moderately dense agriculture	0.75	0.1	20	10	No
Dominant pasture	0.5	0.1	5	5	No
Mixed pasture	0.75	0.1	15	10	No
Mixed savannah	1	0.1	60	30	No
Forests	0.2	0.1	100	50	No
Savannah	1	0.1	60	30	No
Mangroves	0.2	0.1	100	50	No
Rocky and bare soil	0	0	0.1	0.1	Yes
Quarries	0	0	5	5	Yes
Beaches and sand dunes	0	0	5	5	Yes
Saline zones	0	0	3	3	Yes
River beds and alluvial deposits	0	0	2	2	Yes
Water	0	0	5	5	Yes
Wetlands	0.1	0.1	30	15	No

Notes: r_{max}: Maximum current annual increment as percentage of stock. K (carrying capacity): Maximum achievable aboveground woody biomass stock given a certain class of Land Use and Land Cover, plus any other biophysical constraints. K is assumed to remain constant in time. SD: Standard deviation of values used in Monte Carlo realizations. Categories considered as Trees Outside Forest (TOF) are considered sources of wood but are not prone to degradation or deforestation (i.e. renewable by definition).; in these cases K represents wood supplies from pruning or readily available as dead wood.

Appendix C

Mapping charcoal production areas

Expert knowledge approach

To ensure the model accurately depicted charcoal production regions both historically and into the future, we reviewed historical assessments and solicited expert opinion. Assessments carried out in the 1970s and 80s identified several regions as charcoal “hotspots” shown in Figure 11a and b (Voltaire 1979; Stevenson 1989).

For this study, these historical maps were updated by one author (AT) through consultation with multiple sources, including the literature, field site visits, informal unstructured interviews at urban charcoal depots and maritime wharfs, and analysis of satellite imagery, as well as consultation with other researchers. The main areas identified as current production zones align well with areas identified in the past: specifically the regions in the Northern and Southern peninsulas and the island of La Gonâve (Figure 12). Note, Figure 12 represents generalized areas and the boundaries should not be considered definitive in any sense. In addition, the size of each area is not indicative of the volume of charcoal produced there. Actual production volumes are unknown and it is well beyond the scope of this assessment to quantify them.

Figure 11a: Charcoal production sites and transport routes in the late 1970s (Voltaire 1979)

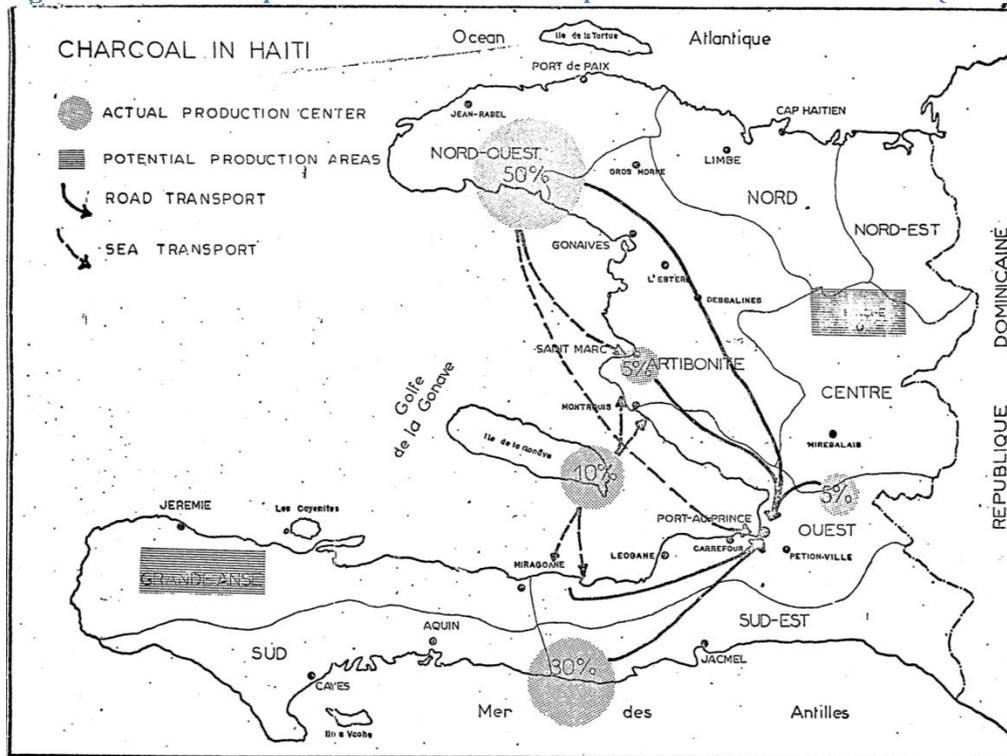


Figure 11b: Charcoal production sites and transport routes in the mid-1980s (Stevenson 1989)

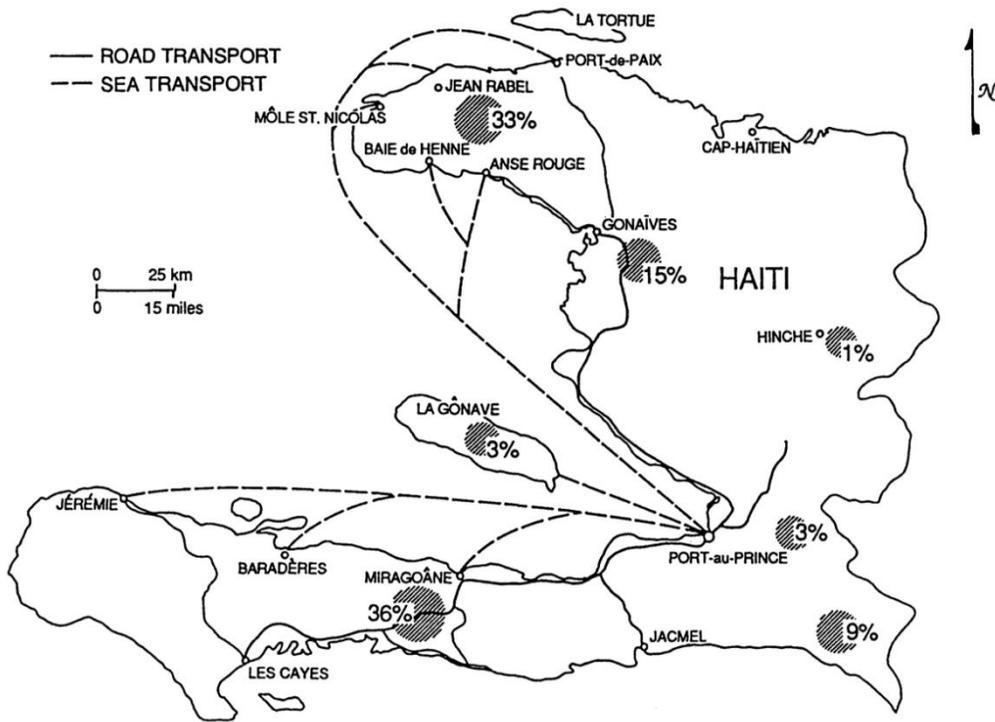


Figure 12: Haitian charcoal production sites at the time of writing (see text for explanation)



Hybrid approach

By means of attraction and friction spatial features that integrates expert knowledge with standard accessibility analysis, charcoal and fuelwood pressure maps were produced. Figures 13 and 14 show both probability maps. Worth mentioning that highly probable areas per se, do not account for availability of woody resources, but depict a “probable willingness” of the local population to gather fuelwood or produce charcoal given there were enough resources.

Figure 13: Harvest pressure for charcoal and commercial fuelwood

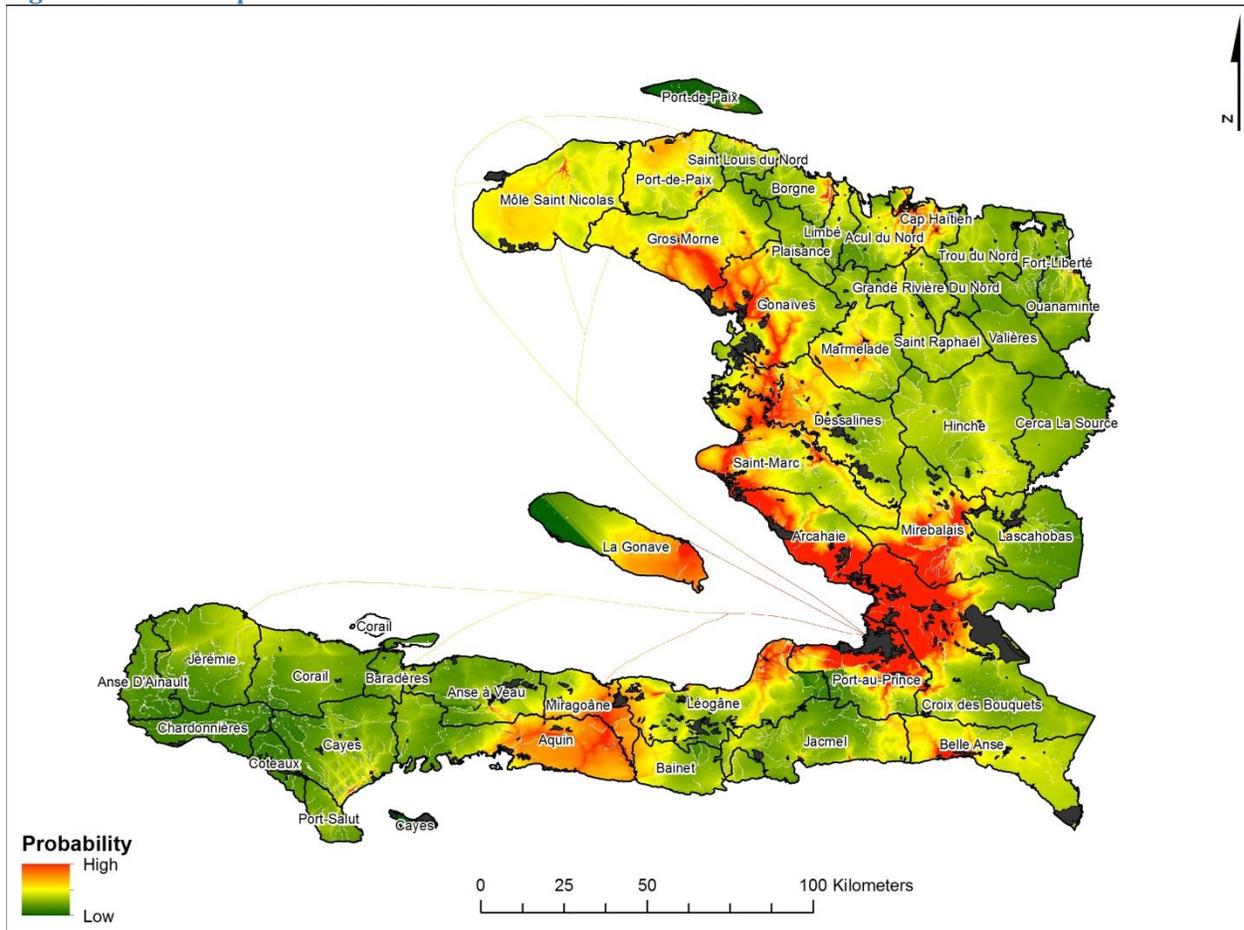
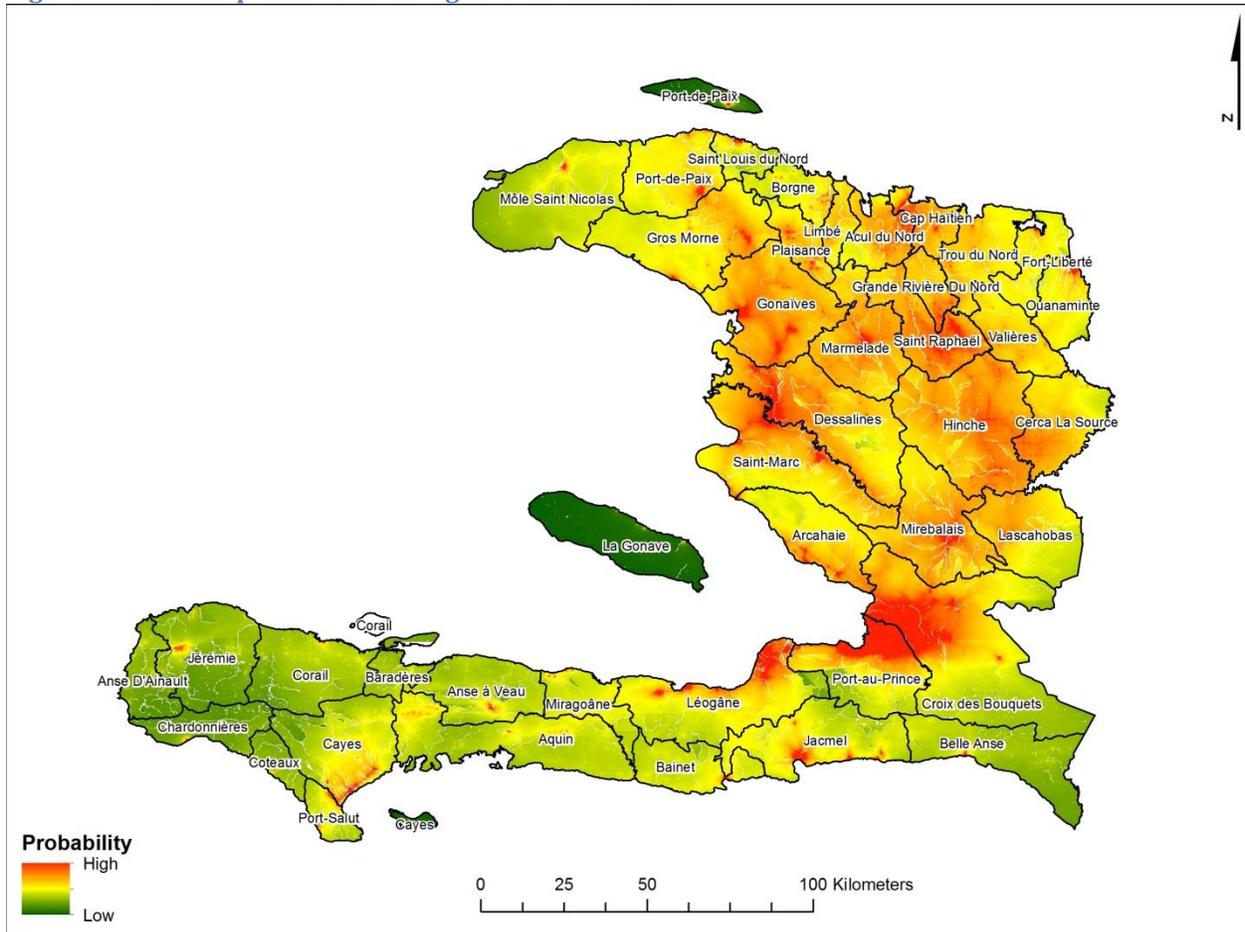


Figure 14: Harvest pressure for self-gathered fuelwood



Appendix D

Table 4: NRB and fNRB as annual average for 24-year simulations (2003-2027)

Scenarios	NRB	NRB SD	fNRB	fNRB SD	Difference between BAU and scenario	Propagated SD of difference between BAU and scenario	Saved CO ₂ in entire simulation period	Propagated SD of saved CO ₂ in entire simulation period
	tDM/yr	tDM/yr	%	%	tDM/yr	tDM/yr	t CO ₂	t CO ₂
BAU	493,835	161,579	9%	3%	0	n.a.	0	n.a.
s1_a	300,861	127,804	6%	3%	-192,974	206,013	-8,844,633	9,442,279
s1_r	444,681	152,585	8%	3%	-49,154	222,238	-2,252,913	10,185,911
s1_b	347,134	136,527	7%	3%	-146,701	211,536	-6,723,808	9,695,382
s1_d	366,495	140,026	7%	3%	-127,340	213,811	-5,836,415	9,799,662
s2_a	440,484	146,883	8%	3%	-53,351	218,363	-2,445,254	10,008,285
s2_c	444,517	146,141	8%	3%	-49,318	217,864	-2,260,400	9,985,445
s3	359,709	152,978	7%	3%	-134,126	222,508	-6,147,445	10,198,298
s4	470,093	157,933	8%	3%	-23,742	225,943	-1,088,168	10,355,736
s5	412,936	147,577	8%	3%	-80,899	218,831	-3,707,872	10,029,733

Notes: SD: Standard Deviation (propagation of error was assumed with no covariance). Values are reported per year for clarity but they are originally calculated as entire simulation results, meaning that NRB correspond to areas with a NET decrease in AGB between 2003 and 2027.

Figure 15: Trajectories for AGB, NRB, fNRB and total fuelwood use in six alternative scenarios (see Table 1 for scenario characteristics)

a

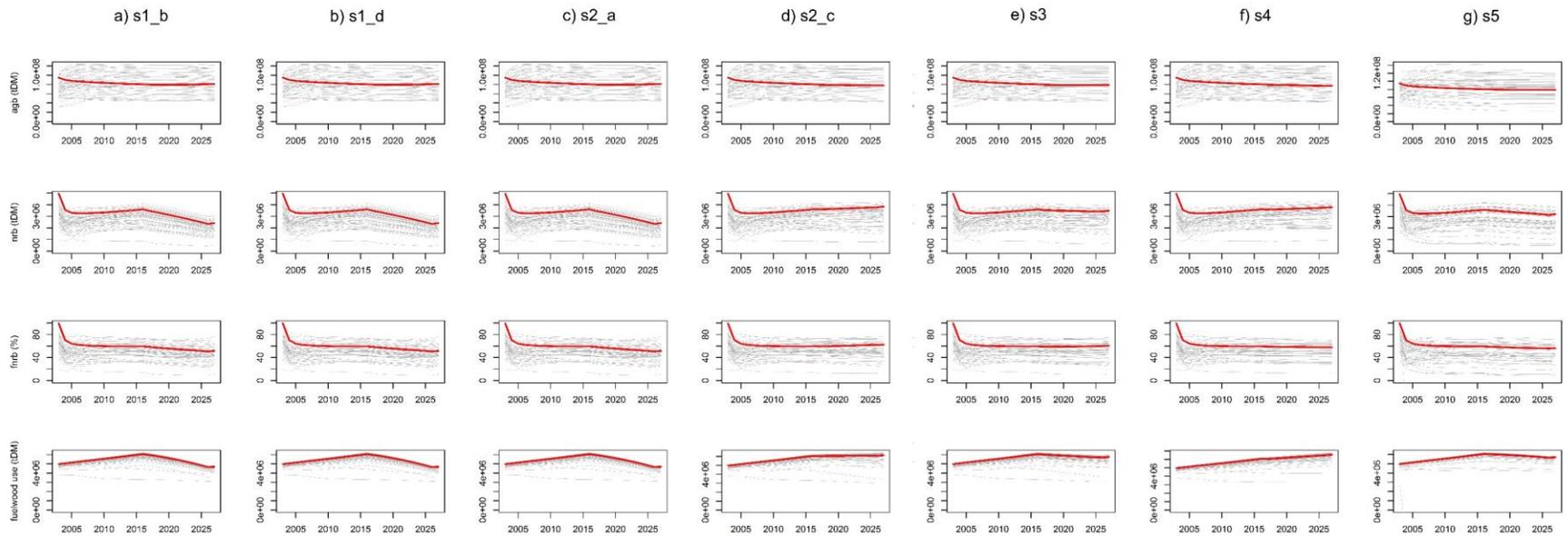
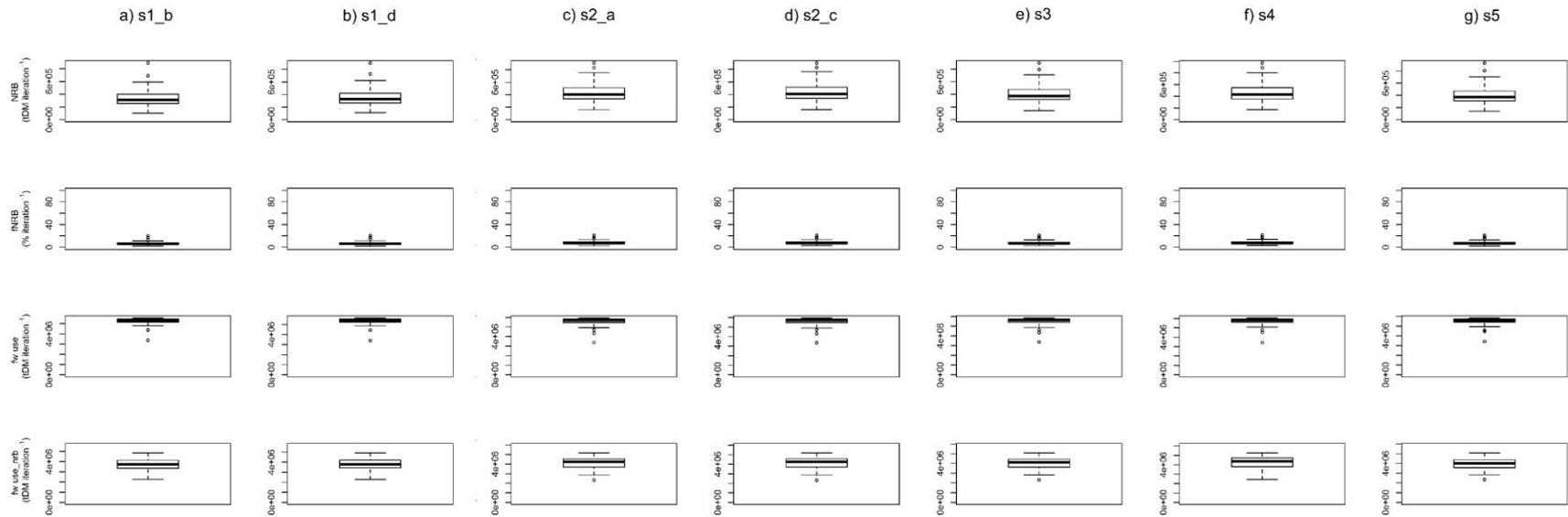


Figure 16: Distributions of NRB, fNRB, fuelwood use and fuelwood use occurring only in NRB pixels in six alternative scenarios (see Table 1 for scenario characteristics)

b



Appendix E

Table 5: Population projections used for scenarios (in thousands)

Year	Urban	Rural	Total
2003	3657	5340	8997
2004	3869	5261	9130
2005	4083	5178	9261
2006	4296	5093	9389
2007	4509	5005	9514
2008	4721	4917	9638
2009	4934	4831	9765
2010	5148	4749	9897
2011	5363	4670	10033
2012	5579	4594	10173
2013	5795	4522	10317
2014	6009	4453	10462
2015	6219	4385	10604
2016	6424	4320	10744
2017	6625	4257	10882
2018	6822	4197	11019
2019	7014	4141	11155
2020	7200	4088	11288
2021	7382	4039	11421
2022	7558	3994	11552
2023	7728	3953	11681
2024	7893	3916	11809
2025	8051	3884	11935
2026	8203	3856	12059
2027	8348	3833	12181