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Sample-Based Estimation of Tree Cover Change in Haiti Using Aerial Photography: Substantial Increase in Tree Cover between 2002 and 2010

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Abstract: Recent studies have used high resolution imagery to estimate tree cover and changes in natural forest cover in Haiti. However, there is still no rigorous quantification of tree cover change accounting for planted or managed trees, which are very important in Haiti's farming systems. We estimated net tree cover change, gross loss, and gross gain in Haiti between 2002 and 2010 from a stratified random sample of 400 pixels with a systematic sub-sample of 25 points. Using 30 cm and 1 m resolution images, we classified land cover at each point, with any point touching a woody plant higher than 5 m classified as tree crown. We found a net increase in tree crown cover equivalent to 5.0 ± 2.3% (95% confidence interval) of Haiti's land area. Gross gains and losses amounted to 9.0 ± 2.1% and 4.0 ± 1.3% of the territory, respectively. These results challenge, for the first time with empirical evidence, the predominant narrative that portrays Haiti as experiencing ongoing forest or tree cover loss. The net gain in tree cover quantified here represents a 35% increase from 2002 to 2010. Further research is needed to determine the drivers of this substantial net gain in tree cover at the national scale.

Keywords: Haiti; deforestation; land cover and land use change; tree cover; forest cover

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1. Introduction

Haiti had 10 million inhabitants in 2011, hence a demographic density of 360 inhabitants/km^2, similar to the density of India and Japan. Despite a continuous urbanization, half of the population still lives in rural areas and depends on individual or family farming for subsistence. At the time of the 2009 agricultural census, nearly 85% of farms had a total area less than 2.5 ha [1]. Farms consisted, on average, of 1.8 parcels, usually located several kilometers away from each other, one of which is the parcel of residence. The average size of a parcel was 0.54 ha. Drought, cyclones, and heavy precipitation are frequent and have severely affected farmers, causing deaths and destroying crops, livestock, housing, and other infrastructure [2,3]. Trees are especially important in this context because, inter alia, they provide food, energy, or income for a large portion of the population; they affect soil moisture, nutrient content and erodibility, reduce vulnerability to weather-related disasters, and influence local and regional climate.

Across the tropics and within specific countries, the ecological role of trees can vary greatly in type and intensity from one situation to another. Trees can be present in many land uses, including but not only in urban land, crop plantations, forestry, agroforestry, as well as in "primary" and naturally regenerated or "secondary" natural forests. Species diversity can also vary largely, as well as patch size and fragmentation, from individual trees to small patches and large areas of tree cover. In general, due to their species richness, natural forests in the tropics and sub-tropics are more resilient and can more easily adapt to disturbances or changes in ecological conditions [4]. Tree species richness, which is typically higher in these natural forests, was also found to be associated with higher levels of carbon sequestration [5,6]. Natural forests are also key for the conservation of biodiversity in the tropics and in Haiti, in particular, given its large number of endemic and endangered species [7].

Planted forests typically contain fewer species than natural forests and have been associated with fewer ecological benefits and with negative ecological impacts, for example on the regeneration of natural forests and on biodiversity [8,9]. With a few exceptions, they are also more vulnerable to disturbances [4]. However, planted forests comprise a wide variety of land uses and land practices worldwide, including productive and protective plantations, and cover "a continuum of situations in terms of species richness and intensity of management" [10]. Even if they cannot perform all roles of a natural, long-lived, diverse forest, depending on their characteristics and environment, planted forests can deliver important net ecological benefits if they are not established through the clearing natural forests. They can sequester carbon, increase forest connectivity, and provide complementary habitat for native species [11]. They can also relieve the pressure on natural forests [12] and facilitate forest succession in the early stages of forest regeneration [13]. In Haiti, trees have been planted for decades as part of reforestation, watershed protection, and soil recovery efforts [14], and include a wide variety of tree species [15,16]. Reforestation could help prevent the extinction of species who don't require primary forests, and the planting of native species could slow or stop a mass extinction that is underway in Haiti [17], which was included in one of the world's biodiversity hotspots [18].

Combining natural forest and planted trees, semi-natural forests, including managed secondary forests and some agroforestry systems, can provide a range of ecological benefits [19] and further contribute to natural regeneration [20,21]. In Haiti in particular, agroforestry can help rehabilitate degraded soil and support reforestation efforts, in addition to increasing and diversifying farmers' income [22].

Deforestation has been considered for many years as a widespread phenomenon in Haiti and as one of Haiti's major development problems. It was widely asserted that "forest" or "trees" have been decimated to the point of covering only 1–4% of the country's land area [23–26]. Haiti was in general portrayed and perceived as a vastly deforested country with few trees left to save, a historical image that has been strongly challenged only recently, based on unprecedented evidence [27,28].

Strikingly, there was for a long time little empirical evidence to support these 1–4% figures. In 1988, Pellek and Talbot [29] stressed the lack of data and adequate methodology to assess the extent of forests and deforestation in the developing world, and in Haiti in particular. He criticized a study by Lewis and Coffey [30], who concluded there was continuous deforestation in Haiti after analyzing three areas representing a very small proportion of the territory. The lack of evidence about Haiti's tree or forest cover was highlighted again in 2010 by Versluis and Rogan [31] and in Haiti's National Forest Resource Assessment (NFRA), which stated that statistics about Haiti's forest cover reported in the literature since the 1980s, often 1% or 2% cover, were the product of guessing [32] (p. 5). Churches et al. [27] found that forest cover statistics on Haiti cited in the literature were not attributed to peer reviewed sources, or to any source at all, and that only two sources of data on Haiti's tree or forest cover existed: a remote sensing study on 2001–2010 woody cover change in the Greater Antilles [33], and a map of Haiti's land cover in 1998 produced by Haiti's National Center for Geospatial Information.

Recently, a few remotely sensed studies assessed tree cover or tree cover change in specific locations in Haiti [31,34]. Nevertheless, Churches et al. [27] and Hedges et al. [7] were the first to use high resolution imagery to estimate Haiti's total tree cover. Their results indicate that Haiti's tree cover in 2010 may have represented as much as 50% of the territory if using a ≥10% tree cover threshold to classify an area as tree-covered, but only 7.5% when using a ≥70% threshold. Regarding empirical assessments of tree cover change in Haiti, Alvarez Berrios [33] mapped the change in woody and shrub cover but based on low spatial resolution imagery (250 m) and using a high ≥80% cover threshold for their woody and shrub cover class. Hedges et al. [7] estimated change in primary forest cover and found that there was a decline from 4.4% in 1988 to 0.32% in 2016. More recently, Pauleus and Aide [35] created land use maps of Haiti based on Landsat imagery and calculated change in forest cover between 2000 and 2015, where forest was defined as areas of natural or semi-natural tall woody vegetation cover (≥5 m) with at least 80% canopy cover. We review the methods and results from all these country-level studies in Section 2 of this paper.

Despite the recent research, there is still no comprehensive assessment of tree cover change including important areas of managed forests, agroforestry, and tree planting in Haiti. Planted trees have been arbitrarily included or excluded from estimates of Haiti's tree cover, without proper justification. Most frequently, planted trees have been omitted due to the adoption of FAO's forest cover definition, which explicitly excludes "tree stands in agricultural production systems, such as fruit tree plantations, oil palm plantations, olive orchards and agroforestry systems when crops are grown under tree cover" [36]. This definition centered on natural forests is not the most relevant or practical one to assess Haiti's tree cover and to inform policies today. Indeed, natural forests were already extensively cleared during colonial times to establish and operate plantations. This loss dynamic continued for over a century following Haiti's independence in 1804, as Haiti became one of the major global providers of wood for some industries, and to reimburse a debt imposed by the French [37]. At the same time, agroforestry emerged with the establishment of *lakou* settlements by escaped and then freed slaves and expanded to become an integral part of peasant farming in Haiti. The *lakou* consisted of clusters of homes and shared plots of land established by a few families, where land transfers were only allowed among members and through inheritance [38]. It became the basic unit of residence, production, consumption, and exchange in Haiti during the 19th century [39].

The *lakou* as a collective family farming unit declined during the 20th century because of internal and external demographic pressure on land [39], but today's individual and family farming systems descend from it and continue to give an important place to agroforestry and to trees in general. Trees are typically present in agroforestry gardens surrounding the residence of the farming household (Figure 1), but also in more distant forestry fallow plots, and occasionally in cultures of annual crops [40]. In addition, trees are also used to demarcate field or property boundaries [14]. Surveys in the 1980s to 1990s indicated forestry fallow periods had been reduced at least in some areas due to population pressure [14], but reportedly mountains are still covered in part by managed forests next to areas of degraded or exposed soil (CEPAL-PNUD 2008 in Jean-Denis [40]). Figure 2 illustrates how four types of cultures or "gardens" are typically implemented across space in a Haitian farm, based on a classification of cultures by Madian-Salagnac [39].

Figure 1. (**a**) On the foreground is an open garden contrasting with a *lakou* garden in the background. (**b**) Internal view of a *lakou* [garden] with its different strata. Photo P. Fernandes (reproduced with permission from Jean-Denis et al. [40], copyright P Fernandes, Cirad, 2014).

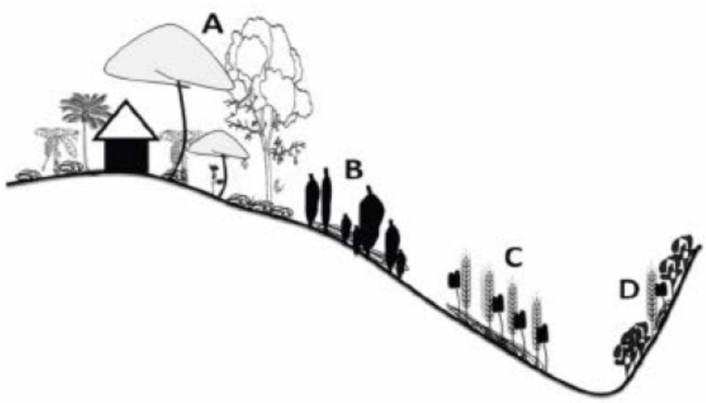


Figure 2. Sketch of spatial distribution of gardens A–D in a typical Haitian farm (reproduced with permission from Jean-Denis et al. [40]).

Tree planting has also been the object of extensive funding from international donors in Haiti since as early as the 1950s [14]. In sum, natural forests have been cleared a long time ago, most rural land is held or used by individual and family subsistence farming plots, and tree planting in these farms is important and supported by international donors. If we take into account this historical decline of natural forests and the importance of trees in Haiti's present agricultural systems it becomes critical that scientists and policy makers move beyond reliance on primarily FAO's statistics on Haiti's forest cover, since the FAO definition of tree cover excludes planted trees outside of forests.

In this study, we take advantage of aerial photography from 2002 made available by Haiti's National Center for Geospatial Information (CNIGS) for this research, and of publicly available aerial photography from 2010, to estimate recent tree cover change in Haiti and evaluate the hypothesis that Haiti's forest or tree cover declined during that period. We take into account all woody vegetation of at least 5 m in height to estimate Haiti's net tree cover change, gross gain, and gross loss between 2002 and 2010. We use 30 cm and 1 m aerial photography to visually classify the land cover of 10,000 points sampled in two stages, a stratified random sample of 400 pixels selected from the Global

Forest Cover Change Product, GFCC [41] and a systematic sub-sample of 25 points within each sampled pixel.

(A) Agroforestry garden, around the residence of the farming households. Includes subsistence crops (banana, plantain, cassava) and cash tree crops (mango, coffee, and citrus).
(B) Annual crops, planted near garden A. Trees are seldomly planted.
(C) Annual crash crops, located further away from the household, on poor soils.
(D) Fallows of forestry, located on slopes of less fertile soils. Long fallows of forestry (trees and bush) are alternated with short cycles of slash-and-burn shifting cultivation.

2. Historical Estimates of Tree Cover in Haiti

Churches et al. [27] estimated total tree cover in Haiti in 2010 through supervised classification of 30 m resolution Landsat images from January 2010 and February 2011, during Haiti's dry season. They used an adaptation of FAO's Land Cover Classification System [42], and the tree height and tree cover thresholds (5 m and 10% respectively) used in the FRA [36]. For comparison of results, they recoded CNIGS's dataset as well as three freely available global land cover datasets: (i) NASA's global land cover (500 m resolution); (ii) GLC2000 Land cover (1 km resolution); and (iii) Globecover (300 m resolution). They found that as much as 32.3 $\pm$ 1.6% of Haiti's land area was tree-covered in 2010. If only patches of at least 0.5 ha are taken into account, 29.4% of Haiti's territory was tree-covered in 2010. Forest cover from the recoded datasets was 26.9% with Globecover, 21.1% with NASA's, and 19.5% with CNIGS. They observed a strong relationship between % tree cover and dataset spatial resolution and attributed it to the fragmented character of canopy cover in Haiti, where small canopy patches can be confused with other land uses at medium and low resolutions.

However, the results of their study are in fact very coarse. If we consider the two extreme cases where (i) 32.3% of pixels have 100% tree cover and the remaining pixels have 10% tree cover, and (ii) 32.3% pixels have 10% tree cover and the remaining pixels have no tree cover, then the possible interval of results is theoretically 3.2%−39.1%. Moreover, the applicability of the reviewed study's results is limited by the use of thresholds. The results mean that 32.3% of 30 m pixels have a tree cover $\geq$ 10% (90 square meters). As shown by Sexton et al. [43] at the global level, the choice of thresholds greatly impacts biomass estimates, with high thresholds leading to underestimation of biomass in areas of intermediate tree cover. Such areas account for more than 99% of Haiti's territory [44]. Conversely, thresholds that are too low for a given context will lead to overestimation of biomass.

Hedges et al. [7] illustrated how changes in % tree cover threshold greatly affect results. They used very high resolution (65 cm) photographs and a systematic grid of 25 cells to visually classify canopy cover within 2000 square polygons of 0.5 ha in size, sampled randomly across Haiti. The grid was applied to each sampled polygon and cells with at least 50% canopy cover were classified as forest, allowing canopy cover to be computed for each location in 4% increments. With this method, they found that 50% of Haiti had a tree canopy cover $\geq$10% in 2010, but only 7.5% had a canopy cover $\geq$70% for example. The sampling protocol used by Hedges et al. [7] follows good practice guidance to generate an unbiased estimator [45], but they did not report the uncertainty for their results. Concerning estimates of tree cover change, Alvarez-Berrios et al. [33] calculated annual land cover at the municipality level for five countries in the Greater Antilles from thematic land cover maps, generated through a supervised Random Forests classification of MODIS MOD13Q1 Vegetation Index product (250 m resolution). In their abstract they write that "In Haiti, the growing population, fuelwood consumption, and increase in agriculture contributed to woody vegetation loss" [33] (p. 81). However, in the body of the article it becomes clear that this net loss highlighted by the authors was calculated by adding the gross changes only of municipalities that displayed a linear change in woody cover between 2001 and 2010 ($p \leq 0.05$ for coefficient of linear regression of woody cover against time). Further, the regression used only the data of municipalities that had at least 3 years of valid data ("valid" meaning that data were available for 99% of the municipality's area). The study does not report how many municipalities were retained this way to calculate net changes in woody vegetation and other land cover in Haiti, but their net change amounts to a loss of just 21 km^2, equivalent to 0.08% of the territory. When taking into account data for all municipalities, they report that woody cover amounted to 7% of the territory in 2001 and increased to 8% in 2010. However, their woody vegetation class underestimates woody cover as it includes only areas with ≥80% woody and shrub cover. Woody plants are also included in their mixed-woody/plantations class which accounts for as much as 28% of the territory in 2001 and 32% in 2010. Most of all, the low resolution (250 m) used for the classification is not adequate to generate an accurate estimate of Haiti's woody cover, which is highly fragmented [27]. This is reflected in the low user and producer accuracies of their woody vegetation class (67.6% and 76.0%) and of their mixed-woody/plantations class (66.0% and 57.9%) for the entire study area.

Hedges et al. [7] estimated for the first time "primary forest" cover and its change in Haiti, from 1988 to 2016, using Landsat imagery. Based on their definition and methodology, primary forest cover in 1988 corresponds to all patches of at least 0.5 ha composed by Landsat pixels that were classified as "closed forest" (70–100% tree cover in natural environments) in at least 4 out of the 5 years 1984–1988 (80% of years). Pixels were classified using a Random Forest prediction model. Pixels not meeting the 80% threshold were masked from the primary forest map for 1988 and for all subsequent years. The same methodology was used to create a primary forest cover map for each year. The authors found that primary forests accounted for 0,32% of Haiti's land area in 2016, down from 4.4% in 1988. Wampler et al. [46] criticized their strict focus on primary forests and conservative definition, which excludes other forest types and makes it "virtually impossible to restore primary forest in Haiti or elsewhere" [p. 1]. Hedges et al. [17] replied that secondary forests were not relevant for their study because most of the biodiversity is in the primary forest, and that their conclusions, the loss of biodiversity should not be "sugarcoated". In reality, both primary and other forests are important for Haiti, and while primary forests are critical for preserving Haiti's biodiversity, other forests can substantially contribute to this end (as Hedges et al. themselves emphasize [17]) and are of great ecological and socio-economic importance in Haiti's context.

Most recently, Pauleus and Aide [35] conducted an automated classification of land uses in Haiti using pre-processed Landsat imagery from Google Earth Engine and high-resolution imagery in Google Earth for training and validation and found that forest cover decreased from 26% in 2000 to 21% in 2015. The result—a high forest cover percentage—is surprising considering their definition of forest, which includes natural and semi-natural woody vegetation, uses a high canopy cover threshold of at least 80% canopy and excludes tree plantations. There appears to be important shortcomings in their methodology. The definition of some land cover classes is imprecise, and the classification system is not exhaustive. For example, there seems to be no land cover class for a forest cover inferior to 80% or for a shrub cover inferior to 80%, and it is not clear which class agroforestry belongs to. Further, they used collections of multi-temporal images for a 12-month period, while only images taking during the dry season should be used to avoid errors from increased vegetation during the wet seasons.

Finally, tree cover change can be derived from GFCC [41], the highest spatial resolution (30 m) dataset currently available at the global level. According to this map, using a >10% tree cover threshold, Haiti had a tree cover equivalent to 39.6% of its territory in 2000 and 33.4% in 2010. GFCC uses a definition of tree cover (all vegetation taller than 5 m in height) that accounts for all types of trees. However, the resolution is not adequate to capture individual trees or groups of trees outside of forests, nor does it provide for an exact estimate of tree cover (independent of a % cover threshold), which is the goal of this study. Area estimates derived from counting GFCC map pixels have unknown uncertainties and biases at the country level. As recommended by good practice guidance [45], land cover and change area estimates need to be based on a probability sample instead of map pixel counting. For these reasons we do not seek to further compare our results to those from Hansen et al. [41] in this study, but instead use the GFCC product to construct strata so as to improve the precision of our sample-based estimates, following established good practice guidance.

3. Study Area

Haiti is located between 18 and 20 degrees north and 71 and 75 degrees west, on the Hispaniola Island, which it shares with the Dominican Republic at its east. Its territory occupies 27,750 km^2, an area comparable to Albania in Europe (28,748 km^2), Burundi in Africa (27,834 km^2, the State of Massachusetts in the United States (27,336 km^2), or Armenia in Asia (29,743 km^2). Its soils and climates vary significantly [47]. About 80% of Haiti's territory has a limestone substrate; the remaining 20% has alluvial or basaltic substrate (Ehrlich et al. 1985 in [23]. The climate ranges from tropical to semi-arid, with a dry season in January to February and two to three rainy seasons approximately from March to June, July to September, and October to December. The most common "life zones" as defined by Holdridge [48] are subtropical moist forest and subtropical dry forest; subtropical wet and rain forest zones are common in the middle-high and high altitudes [23]. It is a country dominated by mountains; about 63% of the land area has a slope greater than 20%, and only 29% has slopes of less than 10% (UNCCD in Hylkema [26]).

4. Materials and Methods

4.1. Data

We used the Hansen et al. [41] Global Forest Cover Change product (GFCC) to define forest cover change strata used in the sampling design. The GFCC is a 30 m resolution product that mapped tree cover extent, loss, and gain. It defines trees as all vegetation taller than 5 m in height; forest loss as a stand replacement disturbance; and forest gain as a non-forest to forest change. For the visual interpretation of the sample, we used two collections of cloud-free aerial photography covering the entire country, with both collections provided by CNIGS: (i) one collection of 1 m resolution orthophotos taken in one day in January 2002, containing 3 bands (RGB); and (ii) one collection of 30 cm resolution orthophotos taken one day in January 2010, containing 4 bands (RGB and NIR).

4.2. Sampling

For the first stage of the sampling, we selected a stratified random sample of 400 pixels of 30 m $\times$ 30 m within Haiti's national boundaries. Using the Hansen et al. [41] GFCC product for the time period 2000 to 2012, we divided the population of GFCC pixels located within Haiti into four mutually exclusive strata: (i) pixels for which there was forest cover loss between 2002 and 2010; (ii) pixels for which there was forest cover gain between 2000 and 2012; (iii) pixels adjacent to pixels for which there was forest cover loss or gain; and (iv) all other pixels. We allocated the 400 sample pixels to strata (Table 1) following the guidelines of optimal allocation [49] and targeting the estimates of forest loss and forest gain. In the optimal allocation formulas applied during the design planning stage, it was necessary to specify the proportion of area of each stratum that the target class was expected to cover. Because the sample data have not yet been obtained, these proportions must be chosen based on the anticipated results. For estimating forest loss as the target, we specified these proportions as 0.6 (forest loss stratum), 0.0001 (forest gain), 0.1 (buffer), and 0.0001 (no change, no buffer). These proportions represent user's accuracy of 60% for forest loss, 10% capture of forest loss by the buffer stratum, and forest loss omission error of 0.01% for both the forest gain and the no change/no buffer strata. For estimating forest gain, we simply switched the proportions to 0.0001 for the loss stratum and 0.6 for the gain stratum, indicating an anticipated user's accuracy of 60% for forest gain. These proportions were selected to be reasonable expectations based on anticipated accuracy of the map area of Haiti, for example user's accuracy of forest loss and forest gain of 60%. Note that if the anticipated strata proportions used in the sample size and allocation planning decisions turn out to be different from the actual proportions in the study area, this will diminish the precision of the estimators but will not introduce any bias in the estimators. The final sample allocation was chosen taking into account the optimal allocation results for estimating forest loss and forest gain. The size of the first-stage sample (400 pixels) was chosen to be large enough to yield an acceptable relative standard error of approximately 20% (ratio of standard error to targeted estimate), but also taking into account that the effort to collect the data must be practically manageable given available resources.

Table 1. Size and proportion of each stratum in the population and in the selected sample.

Stratum	Number of Pixels in the Population	Stratum National Weight	Number of Pixels per Strata Depending on Allocation Method	
			Proportional Allocation	Allocation Used for the Study
Loss 2002–2010	232,673	0.00626	3	80
Gain 2000–2012	64,137	0.00173	1	60
1-pixel buffer around loss and gain	1,056,784	0.02844	11	120
Everything else (no change, no buffer)	35,803,708	0.96357	385	140
Total	37,157,302	1.00000	400	400

The reasons for selecting a stratified random sample were to reduce the standard errors of the tree cover and tree cover change estimates and to include in the sample a sufficient number of pixels for which there had likely been a change in tree cover, since the purpose of the study is to estimate change. Indeed, had we implemented simple random sampling or proportionally allocated stratified sampling, we would have obtained only 4 pixels classified as tree cover change by the GFCC product out of 400 pixels, instead of 140 in our sample. Figure 3 shows the population of pixels considered for the study, per strata, and Figure 4 shows the spatial distribution of the sampled pixels across Haiti's territory.

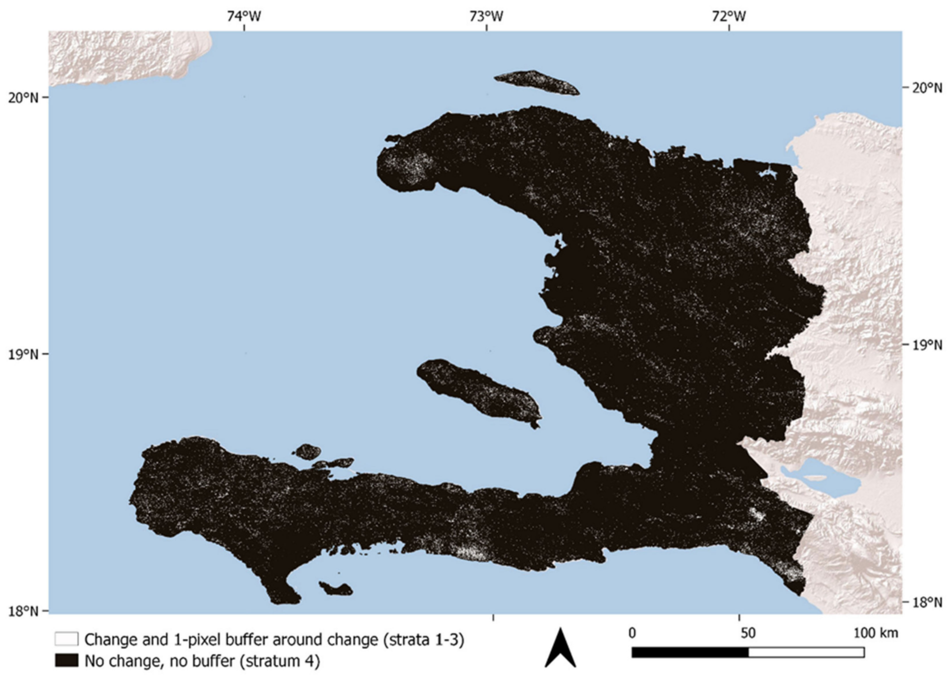


Figure 3. Map of GFCC pixels in the study's area, change and no change strata.

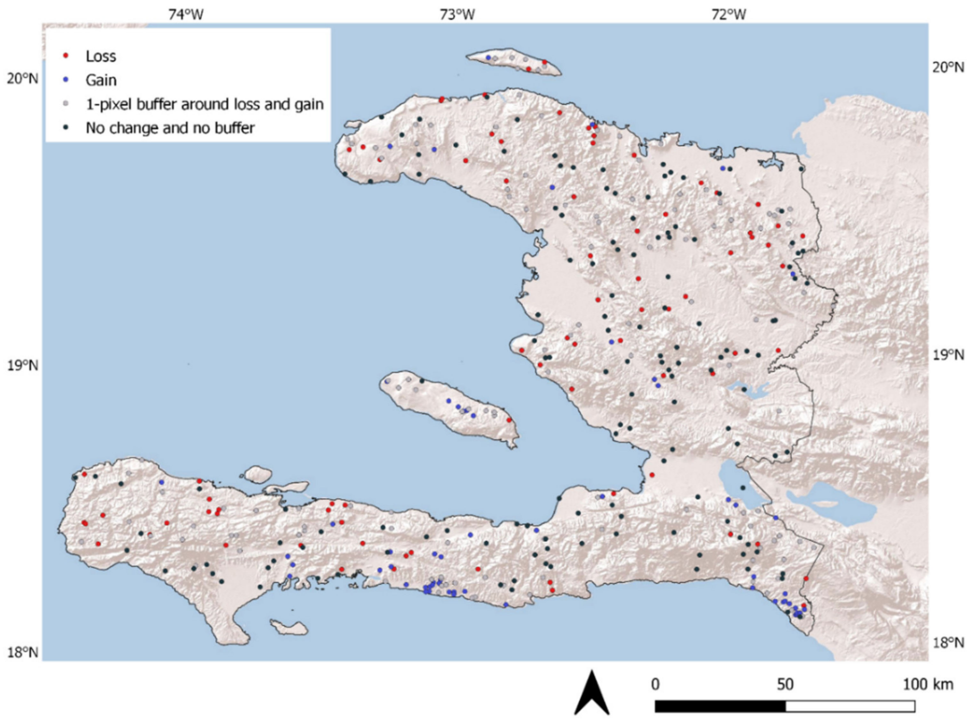


Figure 4. Map showing the location and stratum of pixels sampled from GFCC. The color reflects the stratum from which the pixel was sampled.

For the second stage of the sampling design, we sampled 25 points (geographical coordinates) within each pixel of the first-stage sample, by dividing each pixel using a regular orthogonal 5 × 5 grid and by using the geographical center of each cell as a sample point (see Figure 5). The size of the sub-sample, 25 points, was chosen as a compromise between optimizing the sampling interpretation effort and reducing the variance from the second stage of the sampling.

Figure 5. Example of a sampled pixel (red square) and its sub-sample (25-points).

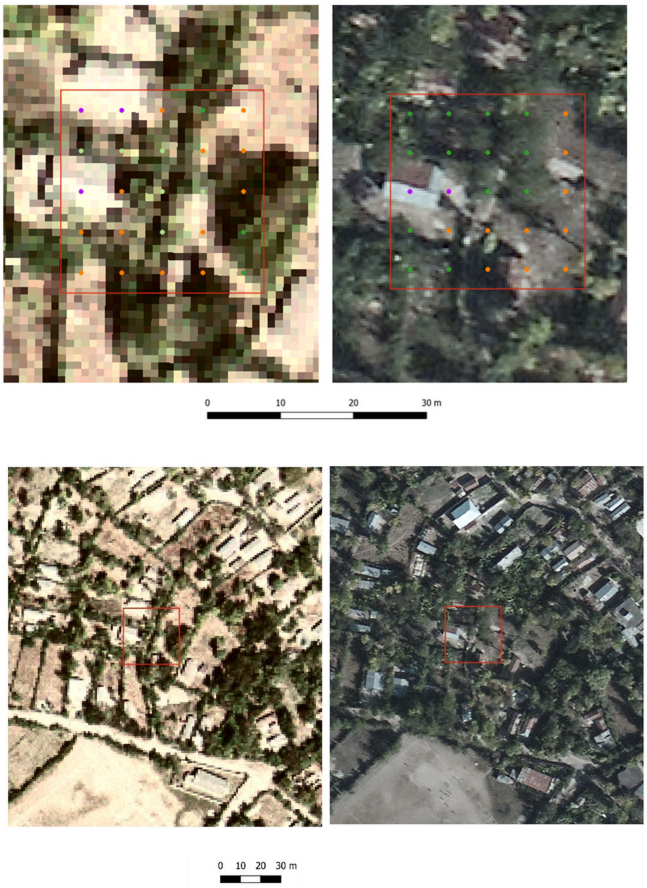
4.3. Land Cover Classification

Before proceeding to the visual classification, we verified the alignment of the 2002 images with the 2010 images by identifying visible concrete buildings and paved roads that did not change over time, and by overlaying images (an example is shown in Figure 6). For each one of the 400 sampled pixels we identified the 2002 and 2010 photographs that contained the pixel's location, displayed both photographs in QGIS, and overlaid the pixel borders and the 25 sub-sample points over the images. We attributed a land cover class (Table 2) to each of the 10,000 sampled points in 2002 and in 2010 by visually examining the 2002 and 2010 orthophotos. We used a 5 m height threshold in our definition of the tree crown class to be able to compare our results to those of other studies, since it is a commonly applied threshold, for example used by Hansen et al. [41] and in FAO's classification. We examined land cover within the pixel, and we also used the area surrounding the pixel to provide context to assist in deciding the class. The land cover class attributed to a point corresponded to its underlying land cover. Examples of sample visualization and classification are provided in Figure 7. Due to limited time and resources and to ensure consistency in the interpretation, the visual classification was performed only by one individual. However, potential interpretation errors (see last column of Table 2) can be deemed significantly limited by the method (visual classification using very high-resolution imagery), and by the fact that tree crowns as defined are easily distinguishable with the naked eye and would be difficult to delineate with precision using automated classification techniques. Given the methodology as a whole, we consider errors of sample interpretation to be negligible compared to our sampling errors, which we estimate following best practice, as explained below.

Figure 6. Example of verification of alignment of 2010 image with 2002 image. The 2010 image is displayed in RGB with 70% opacity, on top of the 2002 image, which displayed in RGB with 100% opacity. The buildings' roofs in 2002 and 2010, visible in white, are well aligned. (Image coordinates: minimum latitude 18.993, maximum latitude 18.993; minimum longitude −72.391, maximum longitude −72.390).

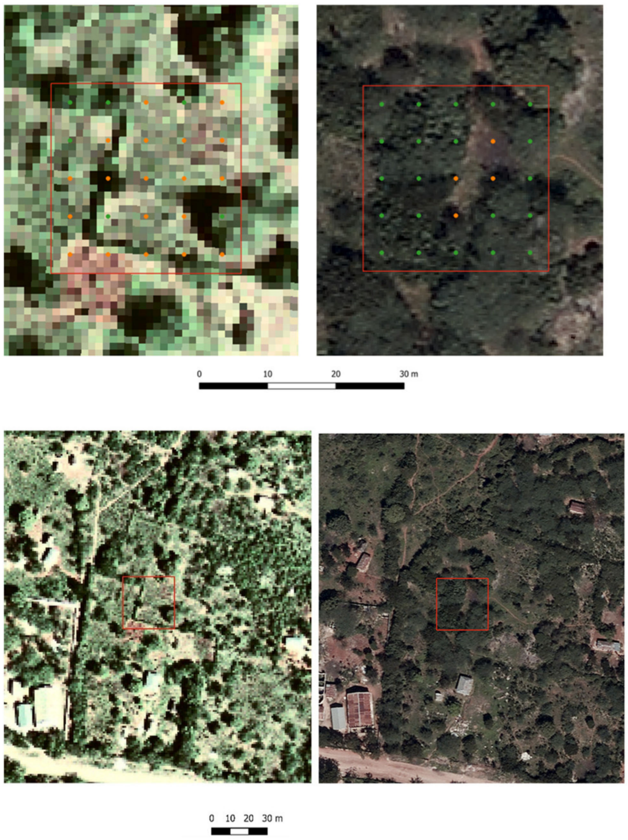
Table 2. Land cover classes, definitions, and potential sources of commission or omission errors.

Code	Land Cover Class	Definition	Visual Elements Used to Identify Land Cover	Classes with Which the Class Can Be Confused
1	Tree crown	Woody vegetation exceeding 5 m in height. Includes fruit-tree plantations.	Geometric form of a tree crown, relatively vivid green color on RGB or red on NIR, the object appears taller than others, often juxtaposed with a shadow.	Other woody vegetation
2	Other woody vegetation	Woody vegetation shorter than 5 m in height. Includes shrub cover.	The object appears shorter than others, less vivid green or red color, may be juxtaposed by a shadow but of smaller size then trees.	Tree crown Bare soil
3	Bare and non-woody vegetation	Includes agricultural land in fallow or cultivated; all non-agricultural non-woody vegetation; and natural bare ground	Relatively homogeneous areas, without the shape of a tree crown and without a shadow, colored with a vivid green, reddish-brown, beige or gray in RGB.	Other woody vegetation
4	Infrastructure	Paved roads and man-made structures	Appearance of a man-made structure based on shape and color.	None
5	Water	Rivers and lakes	Large or long homogeneous shapes of blue or dark color that may exceed the size of the pixel	None
0	Uninterpretable	The land cover cannot be visually interpreted	Shadow from geographical formations such as mountains, inter alia. Or, no DN value for the pixel area (damaged photos).	Any other class



(**a**) Sample no. 272 (pixel-center coordinates: latitude 18.993875, longitude −72.394125)

Figure 7. *Cont.*



(**b**) Sample no. 96 (pixel-center coordinates: latitude 18.226875, longitude −73.211375)

Figure 7. Examples of sample unit visualization and of land cover classification using 25-point grid and orthophotos from 2002 (pictures on the right) and 2010 (pictures on the left). Pixel size: 0.073 ha. Pixel boundaries are traced in red. For each sample unit (No. 96 and No. 272), the two pictures at the bottom show the pixel visualized within its context, and the two pictures at the top show the land cover classification.

4.4. Estimation of Tree Cover and Tree Cover Change

For each one of the 400 sampled pixels, we calculated 5 metrics: (1) tree cover in 2002; (2) tree cover in 2010; (3) tree cover gain 2002–2010; (4) tree cover loss 2002–2010; and (5) net tree cover change 2002–2010. We calculated these metrics as an estimated proportion of the pixel area (i.e., the proportion of the 25 sub-sample points within each pixel), as well as in hectares (by multiplying the proportion by the average pixel area). We estimated the same metrics for each stratum, as the sum of values of pixels in the stratum. Finally, we estimated Haiti's total tree cover in 2002 and 2010, as well as tree cover gross gain, gross loss, and net tree cover change, as the weighted sum of stratum estimates. We used the same calculations to estimate the same 5 metrics for each one of the other land cover classes. The formulas for all calculations are included in Appendix A.

4.5. Estimating Standard Errors

The reported estimates of 2002–2010 tree cover change at the national level are accompanied by their estimated standard errors and resulting 95% confidence intervals. First, we calculated $\hat{V}$, the estimated variance of the national estimate, as the sum of the estimated variances over all strata. The variance for each stratum was calculated as the sum of the variance from the first stage of sampling and of the variance from the second stage of sampling, using an equation derived from Cochran [49], included in Appendix A. We calculated the standard error (SE) of our national estimate of tree cover change as the positive square root of the variance of the national estimate $\hat{V}$.

Finally, we calculated the upper and lower limits of a 95% confidence interval for our national tree cover change. Using the same equation derived from Cochran [49] we estimated the variance, the standard error, and 95% confidence interval for each one of our 5 metrics (cover in 2002, cover in 2010, net cover change, gross gain, and gross loss) for each land cover class.

4.6. Comparison with Other Sources of Data

In order to compare our results to those of Churches et al. [27] and Hedges et al. [7], we would have had to reclassify every pixel in our sample with a tree cover ≥10% as tree-cover, and every pixel with a tree cover <10% as other cover, before re-calculating our total tree cover estimate for 2010. However, we could not use an exact ≥10% tree cover threshold because our tree cover at the pixel level was estimated in 4% increments due to the sub-sample within each pixel consisting of 25 points. Consequently, we used the closest possible threshold below 10% (tree cover ≥ 8%) and the closest possible threshold above 10% (tree cover ≥ 12%) to do two separate reclassifications of our sample. Using the reclassified value of every pixel (0 for other cover, 1 for tree cover) we estimated total tree cover in 2010, as well as the 95% confidence interval based on the ≥8% tree cover threshold, and then tree cover in 2010 and the 95% confidence interval based on the ≥12% tree cover threshold. One major difference remained: Churches et al. [27] did not include fruit tree plantations in their tree cover category, whereas we included any trees of at least 5 m in height. We consider this important difference in our discussion.

5. Results

Based on our sampling and visual classification, there was an extensive net gain in tree cover of 134,362 hectares in 2002–2010, equivalent to 5.0 ± 2.3% of the territory (±value to construct the 95% confidence interval). Relative to the 2002 estimate, the 2010 estimate indicates that the total area covered with trees was as much as 35% higher in 2010 than in 2002. Estimated gross tree cover loss corresponded to an area of 109,494 hectares, equivalent to 4.0 ± 1.3% of the territory, while the estimated area of gross tree cover gain was 243,857 hectares, equivalent to 9.0 ± 2.1% of the territory.

Regarding tree cover each year, the estimated percent tree-covered area in Haiti was 14.3 ± 3.9% in 2002 (387,865 ± 106,302 hectares) and 19.3 ± 4.5% in 2010 (522,227 ± 121,069 hectares). When each pixel was converted to a binary tree cover/no tree cover classification, using a threshold of ≥8% resulted in the 2002 and 2010 tree cover estimates increasing to 38.9 ± 7.8% and 43.8 ± 7.9%, respectively. Using the ≥12% threshold, the 2002 and 2010 estimates were 33.2 ± 7.5% and 42.3 ± 7.9%, respectively.

The results for all other land cover classes used in our classification are summarized in Table 3. Of importance for our tree crown cover estimate, 3.2 ± 1.8% of the territory was uninterpretable in 2002, and 2.8 ± 1.7% in 2010. Sample points were classified as uninterpretable for two main reasons: either (i) the image file contained no data (0.75% of sampled points in 2010 only), or (ii) it was not possible to determine the land cover type, often due to the presence of a shadow on the image but also because the context and location appearance did not allow distinguishing between two or more land cover types.

Table 3. Land cover and land cover change estimates (% of Haiti's area) with 95% confidence intervals in brackets, for each land cover class.

	Tree Crown	Other Woody	Bare & Non Woody	Infrastructure	Water	Uninterpretable
2002	14.3 [10.4; 18.3]	5.3 [3.1; 7.5]	74.8 [69.9; 79.7]	0.4 [0; 0.8]	2.0 [−0.17; 4.1]	3.2 [1.3; 5]
2010	19.3 [14.8; 23.8]	4.1 [2.3; 5.8]	70.4 [65.1; 75.8]	0.7 [0.2; 1.2]	2.8 [0.1; 5.5]	2.8 [1; 4.5]
Net change	5.0 [2.7; 7.3]	−1.3 [−3.1; 0.6]	−4.4 [−7.6; −1.1]	0.2 [−0.1; 0.5]	0.8 [−0.57; 2.21]	
Gain	9.0 [6.9; 11.1]	2.6 [1.5; 3.7]	7.4 [5.5; 9.3]	0.4 [0.1; 0.7]	0.9 [−0.5; 2.3]	
Loss	4.0 [2.8; 5.3]	3.9 [2.2; 5.6]	11.8 [9.2; 14.3]	0.2 [0; 0.3]	0.1 [−0.1; 0.2]	

6. Discussion

6.1. Comparison with Previous Estimates

Table 4 reports different empirical estimates of Haiti's tree cover in 2010 derived from land cover classification studies that used FAO FRA's ≥10% tree cover threshold, but that did not use the same unit area, spatial resolutions, and tree types. The difference between our results and those of Churches et al. [27] in 2010 is mainly attributable to the spatial resolution of images used for the classification, and not to the fact that they excluded fruit trees from their tree cover class. Indeed, there is no assessment of how effectively their classification managed to prevent planted trees from being classified as trees. Hedges et al. [7] did not report a confidence interval. Despite our methodology being similar to theirs, their estimated 2010 tree cover is lower than ours but falls within our 95% confidence intervals when applying the ≥8% and ≥12% tree cover thresholds.

Table 4. Estimates of Haiti tree cover in 2010, derived from remote sensing studies.

Source	Tree Cover (% of Units Where Tree Cover ≥10%)	Spatial Resolution of Images Used for Classification	Area of Unit Used for the Classification	Types of Trees Included in the Tree/Forest Class	Data Collection Method
This study	43.8 ± 7.9% (≥8% threshold) 42.3 ± 7.9% (≥12% threshold)	0.3 m	0.09 ha	All woody vegetation, including palms and fruit trees	Visual interpretation, sample
Hedges et al. [7]	50%	0.65 m	0.5 ha	Includes palms, fruit trees and cacti, but not *Musa* species (banana, plantains) or bamboo	Visual interpretation, sample
Churches et al. [27]	32.3 ±1.6%	30 m	0.09 ha	Does not include fruit-tree plantations. Includes mangroves.	Supervised classification of entire area

Hedges et al. [7] showed how much changes in % cover thresholds affected estimates of Haiti tree cover but did not report a precise estimate that was not based on thresholds. In our study we found that without using thresholds and by accounting for all individual trees of all types, tree cover was estimated to be 19.3 ± 4.5%. Our estimate indicates less tree cover than Churches et al. [27] reported for 2010, but is still much more extensive than what had been asserted for decades. Our results may be a slight underestimate of actual tree cover for two reasons: (i) there were probably trees within our "uninterpretable class" which accounts for up to an estimated 5% of the territory in 2002 and in 2010; and (ii) trees planted on or near crop fields are frequently pruned by farmers and these trees cannot be readily identified on aerial photography.

Although the results from all three studies are much higher than the 3–4% FAO figures repeatedly mentioned in the literature, they do not allow us to disprove FAO's figure and to conclude that tree cover is much higher than previously thought, because we are estimating tree cover based on different objects. FAO's forest class excludes planted trees, while our study and Hedges et al. [7] include them, and Churches et al.'s [27] automated classification may have more or less frequently committed planted trees to their tree cover class. It is possible that forest cover as defined by the FAO still amounts to a negligible proportion of the territory, and we cannot exclude the hypothesis of a decrease in forest cover between 2002 and 2010, based on FAO's definition.

6.2. Consequences and Causes of the Net Gain in Tree Cover

In general, the dramatic net gain in tree cover found here can be seen as potentially positive news. However, as noted above, we cannot exclude the likelihood that natural forests have shrunk during this period, which has negative implications for the environment, especially for biodiversity [7].

To better understand the general environmental implications of our findings it would be helpful to estimate the tree cover change of natural forests separately from that of semi-natural forests and of planted trees. It is very difficult to determine with absolute certainty which trees are managed and which not from remotely sensed data. However, attempts to do so, if accompanied by good practices such as those defined by Olofsson et al. [45], would be relevant for science and policy. They could indicate *to which extent*, *where*, and *when* net tree cover change is the result of a natural or a human process. They could also inform research on factors, of tree cover change, even if the 'proximate causes' and 'underlying forces' of change (terms coined by Geist and Lambin [50]) cannot be fully confirmed and understood without field-based research.

Regarding the causes behind the net gain in tree cover between 2002 and 2010, one possible explanation would be tree growth without human management in many locations, following rural–urban migration and the aging of the farming population. Another potential explanation would be an increase in fallow periods or the planting of trees in a majority of locations, supported or not by external interventions. In particular, Tarter [28,51] and Tarter et al. [52] observed a rise of managed wood lots in Haiti (*rakbwa*), including the establishment of new lots and the natural recovery and re-establishment of old ones to meet an increasing urban demand for wood and charcoal, following the migration to urban areas. This rise of *rakbwa* would have been facilitated by an improvement of existing roads and the addition of new feeder roads. Yet another explanation for the observed gain could be the lifecycle of *lakou* gardens, a theoretical framework elaborated based on field research, and confirmed by Jean-Denis [35], according to which *lakou* gardens evolve following a cycle composed by successive periods of installation, growth, stability, instability, dismantling, and installation due often to natural disasters and disputes over family land. However, these are only hypotheses, highlighting the need for research about tree cover change during other time periods as well as about potential factors behind change, behind the dramatic net gain in tree cover between 2002 and 2010.

7. Conclusions

Using recognized sample-based methods and "good practice" methods [26] and accounting for all types of trees, our study revealed a dramatic net gain in tree cover at the national level in Haiti between 2002 and 2010, equivalent to $5.0 \pm 2.3\%$ of the territory and representing a 35% increase in tree cover. The method is particularly useful for contexts, like Haiti, where tree cover is highly fragmented, and can be easily applied by research and practitioners in other regions of the earth with knowledge of the local context and of statistical methods. Its application is mainly limited by the cost of visual interpretation and by the availability of high-resolution, cloud-free imagery.

Our main finding challenges, for the first time with empirical evidence, the narrative that there has been continuous tree cover loss or deforestation in Haiti. It does not dispute a possible decline in natural forests. Rather, we want to accentuate the importance of using different definitions of "trees" or "forests" for addressing different problems, even within a context, but also of paying attention to these definitions when elaborating narratives, drawing conclusions, or designing policies concerning tree cover change and land cover change in general.

By showing that net national tree cover change is the result of large tree cover losses and gains our study also reminds us of the spatial complexity of tree cover change, i.e., that it is not a unidirectional phenomenon, which is elementary yet seems important to emphasize given how simplistic the deforestation narrative about Haiti has been. Unlike automated classification methods, this sample-based estimation does not provide spatially explicit information on where change is taking place. However, area estimates derived from pixel counting of an automated classification are biased and a sample-based approach using high quality interpretation of the sample points is considered better practice [45].

In the near future, improvements in machine computational ability and learning, the increase in spatial and radiometric resolution of data and increased access to 3D data, as well as the use of different methods, such as Object Based Image Analysis, and of ground data to inform algorithms, should help significantly to enhance the accuracy of automated classifications of tree cover. In the meanwhile, in the face of the growing use and divulging of spatial data by untrained, rushed, but impactful users, automated mapping experiments could include uncertainty metrics at the pixel, administrative, and other levels that are meaningful for users, so that spatially explicit data can be responsibly used.

Finally, there is still little empirical evidence about the temporal complexity of tree cover change at the national level in Haiti. Tree cover change may have occurred at different times within the 2002–2010 study period. For example, locations that experienced tree cover growth between 2002 and 2009, followed by a loss during 2009–2010, are accounted for here as a loss. Moreover, we know little about tree cover change before and after this period. Future research is needed to determine spatial and temporal variations of tree cover change in Haiti and their factors, and to explain net change.

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Appendix A. Formulas for Estimating Area and Standard Errors

A stratified random sample of pixels is selected in which k_h is the sample size from stratum h (h = 1, 2, 3, 4) and there are K_h pixels from which the sample is selected. The subscript i will be used to denote a pixel. A subsample of 25 points is selected within each sampled pixel.

Notation:
K_h = number of pixels in stratum h for the entire study region
k_h = sample size of pixels from stratum h

$p_{h,i}$ = proportion of 25 points in sample pixel i of stratum h that are the class being estimated
A = area of a pixel (0.07286 ha)

The total area of a class (e.g., tree cover loss) is estimated by

$$\hat{Y} = \sum_{h=1}^{4} K_h \overline{y}_h = \sum_{h=1}^{4} \hat{Y}_h \quad (A1)$$

where

$$\overline{y}_h = \sum_{i=1}^{k_h} A p_{h,i} / k_h \quad (A2)$$

is the sample mean area (per pixel) for stratum h, and $\hat{Y}_h$ is the estimated total area for stratum h. The formula for estimating the variance of $\hat{Y}$ requires summing the estimated variances over the 4 strata,

$$\hat{V}(\hat{Y}) = \sum_{h=1}^{4} \hat{V}(\hat{Y}_h) \quad (A3)$$

For each stratum the estimated variance is

$$\hat{V}(\hat{Y}_h) = \frac{A^2 K_h^2}{k_h}\left(1 - \frac{k_h}{K_h}\right) s_h^2 + \frac{A^2 K_h}{k_h} \sum_{i=1}^{k_h} p_{h,i}(1 - p_{h,i})/25 \quad (A4)$$

where

s_h^2 is the sample variance of $p_{h,i}$ for the k_h sample pixels in stratum h. The standard error of the estimated total area is the square root of $\hat{V}(\hat{Y})$ from (A3).

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