Ecological Applications, 15(3), 2005, pp. 1083–1095

CREATING A VIRTUAL TROPICAL FOREST FROM THREE-DIMENSIONAL AERIAL IMAGERY TO ESTIMATE CARBON STOCKS

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Abstract. Given the interest in implementing land-use change and forestry projects for mitigating carbon dioxide emissions, there is potentially a large demand for a system to measure carbon stocks accurately and precisely in a cost-effective manner. As terrestrial ecosystems tend to be heterogeneous, a large number of sample plots could be needed to attain the regulatory-required levels of precision, thus resulting in a costly process. A potential way of reducing costs of measuring the carbon stocks of forests is to collect the key data remotely. We have designed a system (a multispectral three-dimensional aerial digital imagery system, M3DADI) that collects high-resolution overlapping stereo imagery ($\leq$10 cm pixels) from which we can distinguish individual trees or shrubs. In essence, we created a virtual forest that we used to measure crown area and heights of all plant groups. We used this M3DADI system to estimate the carbon stocks in aboveground biomass for the pine savanna in the Rio Bravo Carbon Sequestration Pilot Project in Belize. Seventy-seven plots were established on the images, and using a series of nested plots we digitized the crown area and heights of pine and broadleaf trees, palmettos, and shrubs. Based on standard destructive harvest techniques, we obtained highly significant allometric regression equations between biomass carbon per individual and crown area and height. Combining the image-plot data with the allometric equations resulted in a mean carbon stock of 13.1 Mg/ha with a 95% confidence interval of 2.2 Mg C/ha or $\pm$16% of the mean. The coefficient of variation was high for all vegetation types (range of 31–303%), reflecting the highly heterogeneous nature of the system. We estimated that 202 plots would need to be installed to achieve a 95% confidence interval of $\pm$10% of the mean. We compared the cost-effectiveness of the M3DADI approach with conventional field methods based on the total person-hours needed by both approaches to collect the same set of data for 202 plots. We found that the conventional field approach took about three times more person-hours than the M3DADI approach.

Key words: aboveground biomass; Belize; biomass equations; carbon sequestration; digital imagery; savanna; videography.

Introduction

Interest in implementing land-use change and forestry projects, as a means of mitigating carbon dioxide emissions, has increased markedly during the last five years or so, particularly by nations and private sector companies as they develop strategies to meet anticipated regulatory requirements. With this intention, numerous forest-based pilot projects have been implemented, and many of these projects have accurately measured the carbon benefits to high degrees of precision (Brown et al. 2000*a*, *b*, Brown 2002). However, given the size and heterogeneity of many of these pilot projects, particularly those in the tropics, large numbers of plots have been installed to attain the high levels of precision targeted, resulting in sampling costs of tens of thousand to hundreds of thousand of dollars. With the increasing interest in carbon sequestration projects, there is potentially a large demand for a system to measure and monitor carbon stocks accurately and precisely in a cost-effective manner. The purpose of this paper is to present such a system.

The standards being developed for measuring the potential carbon credits for forest-based activities are based on a statistically determined and distributed set of ground plots with accurate and precise measurements of the carbon stocks in the main forest components over time (Brown and Masera 2003). Ground-based methods for estimating biomass carbon of the tree component of forests are well known and typically are based on measurements of individual trees in many plots combined with allometric equations that relate biomass as a function of a single dimension, e.g., diameter at breast height (dbh), or a combination of dimensions, such as dbh and height. A potential way of reducing costs of measuring and monitoring the carbon stocks of forests is to collect the key data remotely, particularly over large and often difficult terrain where

Manuscript received 14 May 2004; revised 3 September 2004; accepted 8 September 2004. Corresponding Editor: M. Friedl.

the ability to implement an on-the-ground statistical sampling design can be difficult. As remote methods collect data from above the forest canopy, the question is: What data are needed to estimate the biomass carbon of forests directly? Based on previous research on forest biomass (e.g., Brown 1997), we propose that to accurately estimate biomass carbon stocks with high precision from ''overhead'' imagery data requires a measure of the crown area and height of individual trees from many plots in combination with allometric equations based on these dimensions, similar to the ground-based approach.

An investigation of the available aerial and satellite data collecting systems yielded an array of methodologies with varying accuracies and amenabilities for use in carbon studies. The focus of much of the efforts on the use of remote sensing data is for large-scale analyses, generally regional to continental and even global scales. For carbon sequestration activities, the scale tends to focus on well-defined land areas often on the order of thousands to tens of thousand of hectares in size.

Much of the research using coarser remote sensing imagery (e.g., advanced very high resolution radiometer [AVHRR] and Landsat imagery) has focused on developing correlations between some index of the sensor data and ground-based biomass data with the idea that such correlations can then be used to extrapolate to larger areas. The recent availability of higher resolution data from sensors such as IKONOS has renewed efforts to measure crown area or crown diameter of tropical forest trees over large scales with mixed success (e.g., Asner et al. 2002, Read et al. 2003, Clark et al. 2004). Another advance in remote sensing of forest biomass is a scanning laser system such as LIDAR. Tests of this system in temperate conifer and deciduous forests and tropical forests have shown its ability to produce high correlations between the sensor metrics and various indices of forest structure, including aboveground biomass at the stand level (Lefsky et al. 1999, Means et al. 1999, Drake et al. 2002, 2003).

In each of the currently available remote sensing methods, including the use of LIDAR, described above, modeling or calibration using ground-based data at the stand level is required to develop relationships that are then used to infer carbon stock estimates over larger areas. The inability of remotely sensed products currently available to measure simultaneously the two key parameters for estimating forest biomass from above (i.e., tree height and tree crown area) limits their application for measuring carbon sequestration projects to the accuracy and precision needed. Faced with this deficit in the remote sensing arena, we designed a system that integrates available ''off-the-shelf'' technology to collect high-resolution digital imagery ($\leq$10 cm pixels) from which we could distinguish individual trees or shrubs, identify them to plant type (e.g., broadleaf, needle leaf, palm, shrub, etc.), and measure their height and crown area. In essence, we would create a virtual forest that could be used to collect tree measurements. The measurements are then used to derive estimates of aboveground biomass carbon for a given class of individuals using allometric equations. Biomass can thus be measured in the same way as in ground plots, to achieve potentially the same accuracy and precision, but with potentially less investment in resources. In addition the data can be archived so that, if needed, the data could be reevaluated or used for some future purpose.

Our system, a multispectral three-dimensional aerial digital imagery (M3DADI) system, fits on board a single-engine plane and collects digital imagery along statistically located transects (flight paths). The M3DADI system collects overlapping stereo images from a calibrated high-definition video camera to create three-dimensional images that are georectified by internal navigation equipment on the plane. The system also includes a profiling laser to record ground and canopy elevations. Preliminary tests, using an earlier prototype of the system, showed that it has potential for accurately and precisely measuring carbon stocks in forest ecosystems (Slaymaker 1999, Electric Power Research Institute 2000).

We tested this new M3DADI system on one of the existing tropical carbon sequestration pilot projects: the Rio Bravo Carbon Sequestration Pilot Project in Belize implemented by Programme for Belize and The Nature Conservancy. The focus of our study is the pine savanna, a system with pine trees as the dominant vegetation mixed with broadleaf trees, shrubs, palmetto, and grass covering an area of $\sim$5000 ha. The pine savanna is highly heterogeneous, and initial estimates suggest a large number of plots would be required to achieve high precision in carbon stock estimation, thus requiring a large amount of resources. Given these characteristics of the pine savanna we believe that it represents an ideal area for testing our M3DADI system.

The main goals of this study were to determine whether it is possible to accurately and precisely estimate biomass carbon from aerial digital imagery in a cost-effective manner and to investigate how the system could be improved to make it more accurate, precise, and cost effective. To address these goals, we developed a sampling design for collecting and interpreting the aerial digital imagery, including distribution and number of transects and plots and plot area; developed new field-based allometric equations for the main pine-savanna plant components that match the dimensions measured in the imagery; and estimated the carbon stock of the pine savanna. We conclude with a discussion of the system's cost-effectiveness for estimating carbon stocks and the further refinements that could be included to improve the accuracy and precision and reduce cost.

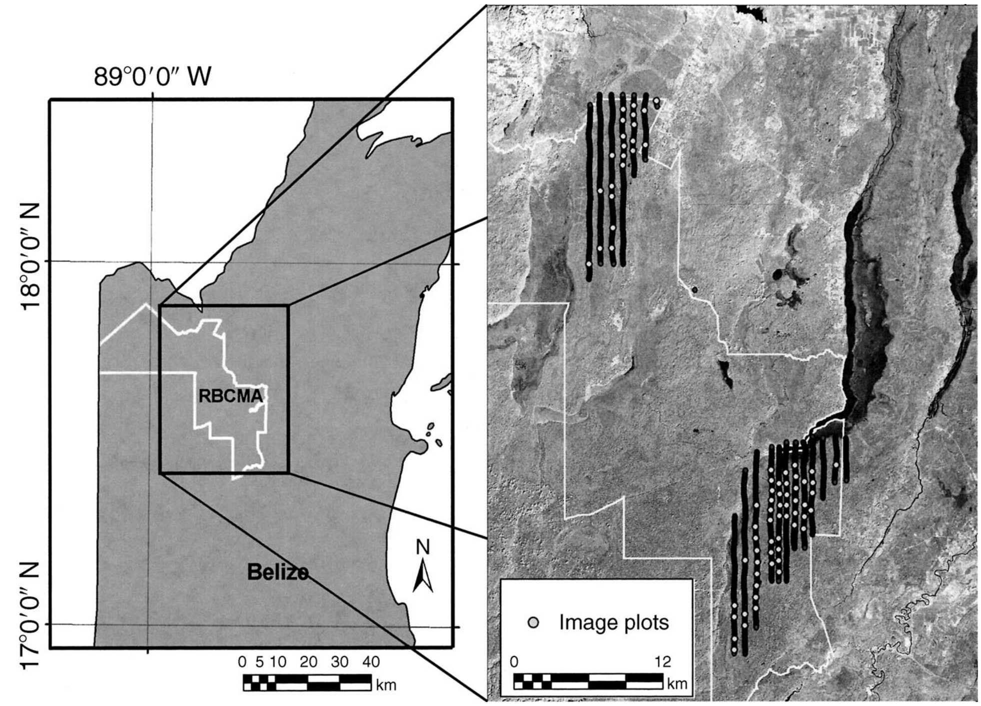

FIG. 1. Location of the study area in Belize showing the area of the Rio Bravo Conservation and Management Area (RBCMA) with areas of pine savanna embedded in the broadleaf forest landscape. The black lines running north and south, composed of many very closely spaced images, are the paths of the flight-line transects over the savanna with the location of the image plots selected for analysis indicated.

METHODS

Study area

The pine-savanna ecosystem in Belize ranges from low-lying coastal savanna plains with few pine trees to denser pine forests in the higher elevations. This ecosystem is adapted to xeric and acidic conditions and is the result of poor nutrient availability, extremes in water availability, and a recurring fire regime (Meerman and Sabido 2001). The area of study is located in the Rio Bravo Conservation and Management Area (RBCMA, Fig. 1). The pine savanna is an important ecosystem within the RBCMA because of the diversity of plant species and habitats for birds and other wildlife. Prior to its acquisition by Programme for Belize, the pine savanna was vulnerable to increased periodicity of fire and encroachment from agriculture. Fire is a natural component of this ecosystem; however, the frequency of fire has exceeded the tolerance of regenerating pines. A management plan has been implemented for the pine savanna in the RBCMA to reduce the fire frequency and severity to adequate levels favoring, but not excluding, the establishment and persistence of the pine ecosystem.

The pine savanna consists of a mixture of pine trees (*Pinus caribaea* Morelet), broadleaf trees (*Quercus* spp. and *Crescentia cujete* L. [calabash]), grasses, shrubs (*Myrica cerifera* L., *Byrsonima crassifolia* (L.) DC, and *Curatella Americana* L.), and palmetto vegetation (*Paurotis wrightii* (Griseb.&Wendl.) Britt.) (Fig. 2). There are four general associations: pine woodland, pine–oak woodland, pine grassland, and shrub grassland. The criteria for delineating these associations is not always clear, and the woody ones often occur in small patches. The palmetto is widespread and occurs in two forms: palmetto thicket where the plants grow over a broad expanse in the shrub grass formation with a low number of relatively short individuals per unit area (Fig. 2C); and palmetto clumps that grow in association with pine woodlands and are taller and densely packed (Fig. 2D).

Annual rainfall is ~1500 mm, with peaks in September and October. The rainfall distribution is seasonal with the dry season extending from March to May and the rainy season from June to February. Minimum temperatures are approximately 18°C and maximum temperatures approximately 34°C, with the higher temperatures generally occurring at the end of the dry season.

The topography is generally flat to undulating, with lower areas near gallery forests and creeks. The pine woodlands are located on slightly higher elevations (20–55 m above sea level). The characteristic quartz sandy soils within the pine savannas occur over a hard pan of clay; consequently they are usually wet in the rainy season with water collecting in depressions. During the dry season the soils are very dry, except in the

FIG. 2. Vegetation of the pine savanna in the Rio Bravo Conservation and Management Area in Belize. (A) General view of the system showing pine trees in the background with dense grass cover in the foreground; (B) *Quercus* species in the foreground with a large pine tree in the background; (C) palmetto thicket; and (D) palmetto clumps associated with the pine woodland.

lower lying areas where the soils remain moist. Wright et al. (1959) characterized the soils as nutrient deficient, acidic, Pleistocene alluvial soils.

Description of the M3DADI system

The essential goal of the M3DADI system is to obtain imagery of the ground at a scale at which individual trees can be identified and measured; from experimental analysis we found that a scale of 10-cm resolution meets this goal. The components of the M3DADI system are a Duncantech high definition video camera (Redlake, San Diego, California, USA), a profiling laser, a Watson inertial measurement unit (Watson, Eau Claire, Wisconsin, USA), a real-time differential correction geographic positioning system (GPS; using Omnistar, a commercial satellite service [OmniSTAR, Houston, Texas, USA]), a laptop computer, and a redundant array of inexpensive drives (RAID) capable of storing terabytes of data (Fig. 3). All incoming data for each exposure are time stamped in the computer. This allows for all data to be associated with each other piece of data and to integrate them into a position report for each exposure.

The Duncantech camera was calibrated before the flight to correct the imagery for the inherent distortion of the camera and lens system. The camera was mounted on a calibration table with its field of view precisely perpendicular to a measured grid pattern on a moveable track. The camera took images of the grid at different known distances along the track, producing a series of lens-field measurements in three-dimensional space. Using software developed in collaboration with H. Schultz (*personal communication*), the inherent distortion produced by the lens and the internal metrics of the camera were calculated and then used to resample each image, removing the effects of that distortion.

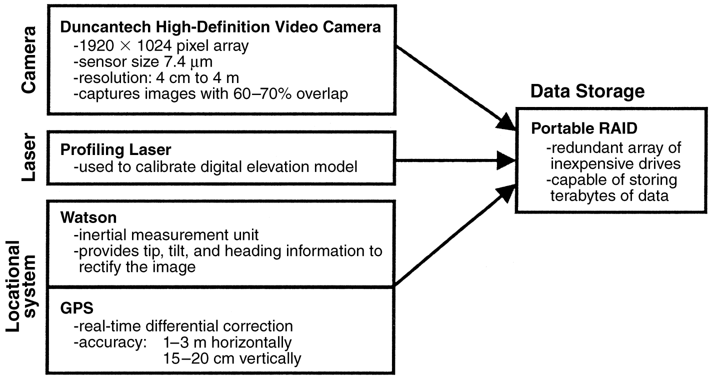

FIG. 3. Overview of the multi-spectral three-dimensional aerial digital imagery (M3DADI) system. The Duncantech is a high-definition video camera, the laser is a profiling one used to calibrate a digital elevation model, the Watson is the inertial measurement unit that provides tip, tilt, and heading information used to properly rectify the imagery, and the geographic positioning system (GPS) collects real-time data from a satellite service. The data are collected with a laptop computer and a portable redundant array of inexpensive drives (RAID) capable of storing terabytes of data if needed. The whole system runs off the aircraft's 12-V power system.

The system can be loaded onto nearly any single-engine aircraft that can fly at low altitudes (approximately 305 m above ground level) and at relatively slow speeds for image acquisition (we typically use a Cessna such as a 182). The M3DADI system can be flown under cloud cover, flown at high temporal frequency, and viewed as automatically georeferenced strips and stereo pairs in a standard computer.

Spacing camera exposures for 70–80% overlap provides the stereo coverage of the ground while the profiling laser, inertial measurement unit, and GPS provide georeferencing information to compile the imagery bundle-adjusted blocks in a common three-dimensional space of geographic coordinates. These block files can be viewed and measured on a computer screen as a series of true optical stereo-image pairs using ERDAS-Imagine Stereo Analyst (Leica Geosystems, Atlanta, Georgia, USA) and Arcview 3.3 (ESRI, Redlands, California, USA). These software programs alternately display the left and right images of each stereo pair at 120 times/s, synchronized through a video card to a pair of shuttered glasses that block the opposing eye for each cycle. Using this equipment, the bundle-adjusted block files can be viewed as a literal three-dimensional virtual forest with an accurate and detailed view of the canopy in which individual trees can be identified and labeled with their crown diameters and areas and heights recorded to annotation files as per the methods developed by Slaymaker (2003).

For the Rio Bravo Carbon Sequestration Pilot Project, a series of systematically spaced parallel transects, at approximately 1 km intervals and 200 m wide, with a random start, were flown over the entire study area to collect imagery at a resolution of 10 cm per pixel (Fig. 1). These images were compiled into block files for direct interpretation in ERDAS-Imagine Stereo Analyst and to generate digital elevation models of each transect that were used to differentially rectify the images into ortho-photographic mosaics of each strip.

Collection of data from the digital imagery

In 2002, we collected and interpreted some digital imagery over the Belize pine savanna using a prototype version of the M3DADI system and preliminary field data. An analysis of 19 image plots resulted in a mean carbon stock of 13.2 Mg C/ha and a coefficient of variation of 42%. Based on this information, we estimated that the number of plots needed for a 95% confidence interval of ±10% of the mean was approximately 70. However, we assumed that a more detailed data collection and analysis in this savanna system would be more variable than indicated by the preliminary analysis and so estimated that 100 image plots would be needed.

A series of image plots were selected along the transects in a systematic manner to ensure a full coverage of the pine-savanna area. We determined the number of images we had collected and the total length of the transects. For a systematic sampling design, we then selected 100 images that were spaced equally along the transects; this step resulted in selecting every 27th image. However, when implemented, this design did not work out exactly as planned for several reasons. A high incidence of fire in the northern section of the savanna led to a disproportionate number of omissions from this region as in this first phase of the work we focused only on unburned areas. On closer inspection of the selected image plots we also found that some of them were located in transition zones between the savanna and broadleaf forest, and these were deleted from the sample. Other image plots were moved one or two images north or south of the designated image because of problems with the image caused by turbulence of the plane (8%). In total 77 image plots were selected and analyzed. (The imagery is archived and new plots could be identified and analyzed as resources allow.)

Each selected image plot was manually interpreted and measured on the corresponding stereo-image pairs in that transect's block file. To efficiently measure a representative sample of the vegetation in each image plot, a series of nested plots was ''installed'' around a plot center that was located at the image center, just as one would do in the field. Three nested plots were used: 8.5 m radius (0.023 ha), 18.5 m radius (0.11 ha), and 28 m radius (0.25 ha) to digitize crown areas (in square meters) and heights (in meters) of the vegetation. The

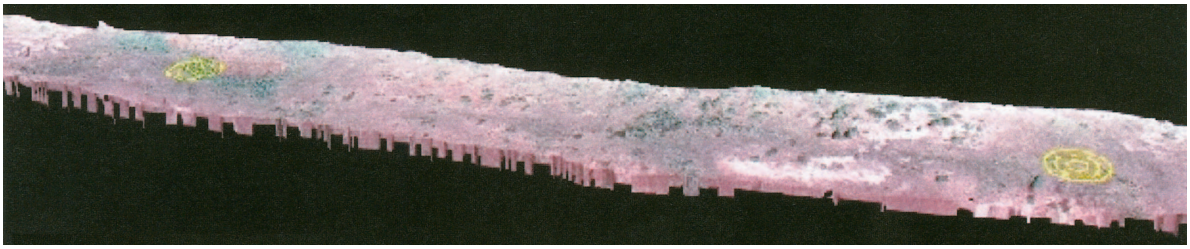

FIG. 4. Illustration of one of the transects showing the nested plot configuration. The green shaded areas represent vegetation, while the brown areas are dried grasses.

smallest plots were used to digitize saplings (<5 m in height), palmettos, shrubs, and grasses (dense or sparse grasses). The crown area and height of broadleaf trees only were digitized in the second nested plot. The largest plot was used to measure all pine trees. In some images, it was difficult to distinguish the difference between pine and broadleaf trees, and in these cases (18% of all plots) all trees were measured in the large plot.

The digitization process began with the creation of the nested plot circles in ArcView 3.3 (Fig. 4). The plot circles were imported into ERDAS-Imagine's Stereo Analyst, where the interpreter then created polygons around the crown of each vegetation type (Fig. 5). After each polygon was created, heights were determined (in the z plane) from measurements of the highest point on the tree crown or mean height of the shrubs and a point in the vicinity for ground height. The resulting databases associated with each plot and vegetation type were then exported into Excel (Microsoft, Redmond, Washington, USA) for analysis.

To quantify the potential error in image interpretation, a subset of 10% of the plots (seven plots) was selected randomly and interpreted independently by a different analyst. The seven plots chosen were well distributed both across vegetation types and across the landscape.

Collection of ground data

To convert the measurements from the imagery (crown area and height) to estimates of biomass carbon, we derived a series of allometric equations between biomass carbon and the imagery measurements. In 2002 and 2003, field measurements were made on the major components of the pine savanna (Table 1).

A total of 53 individual pine trees and saplings were harvested. Before harvesting, their dbh, total height, and crown diameter (two measurements at right angles to each other) were measured. The trees and saplings were harvested, and total aboveground oven-dry mass was determined using standard methods. Twenty individual calabash trees were harvested and measured in the same manner as the pines. Only three oak trees were harvested but the results were used to evaluate the accuracy of existing hardwood equations. Four equations were considered: Schroeder et al. (1997; eastern hardwood equation), Brown (1997; tropical moist equation), S. Brown (*unpublished data,* eastern hardwood height and dbh equation), and Jenkins et al. (2003; hard maple/oak/hickory/beech equation). The equation of Schroeder et al. (1997) was most accurate in predicting the biomass of the harvested oaks and so was adopted. At the time of harvest, 20 additional oak trees (dbh range: 20–53 cm) were measured for tree height and crown area. In this way a relationship could be established between crown area/height and oven-dry biomass (predicted using Schroeder et al. [1997]).

The remaining vegetation groups were shrub, palmetto, and grass. For shrubs we determined that individual plants would be distinguishable in the imagery but that it would not be possible to determine species. Fifty-one shrubs were harvested representing six species. At the time of harvest, crown diameter (shrub crowns were generally elliptical in shape and two measurements in the widest and narrowest directions at right angles were made) and mean height were measured; the shrub was then harvested and oven-dry mass determined using standard methods. Patches of palmettos consist of many stems and even many individuals, which would not be distinguished from one another in the imagery. Consequently we decided to create allometric equations relating the area of a patch and mean height to biomass for palmettos. For each group, subplots of group-specific size were used for the harvest; the subplots were projected vertically forming a virtual cuboid or cylinder in which all vegetation was harvested. As discussed above palmettos on the savanna grow in two forms, thicket and clump. Thickets were sampled by harvesting 40 2×2 m subplots, and clumps were sampled by harvesting 36 1×1 m subplots, including a range of height classes and densities. Grass was divided into two classes, sparse and dense, and harvested in 31 60 cm diameter subplots. In each case, after harvest, oven-dry biomass was determined using standard methods.

Field data analysis

Throughout this study, carbon is assumed to be 50% of the biomass. Regression models were created for the relationship between biomass carbon and a combination of the height and crown area. For the pine and broadleaf trees, we developed relationships between

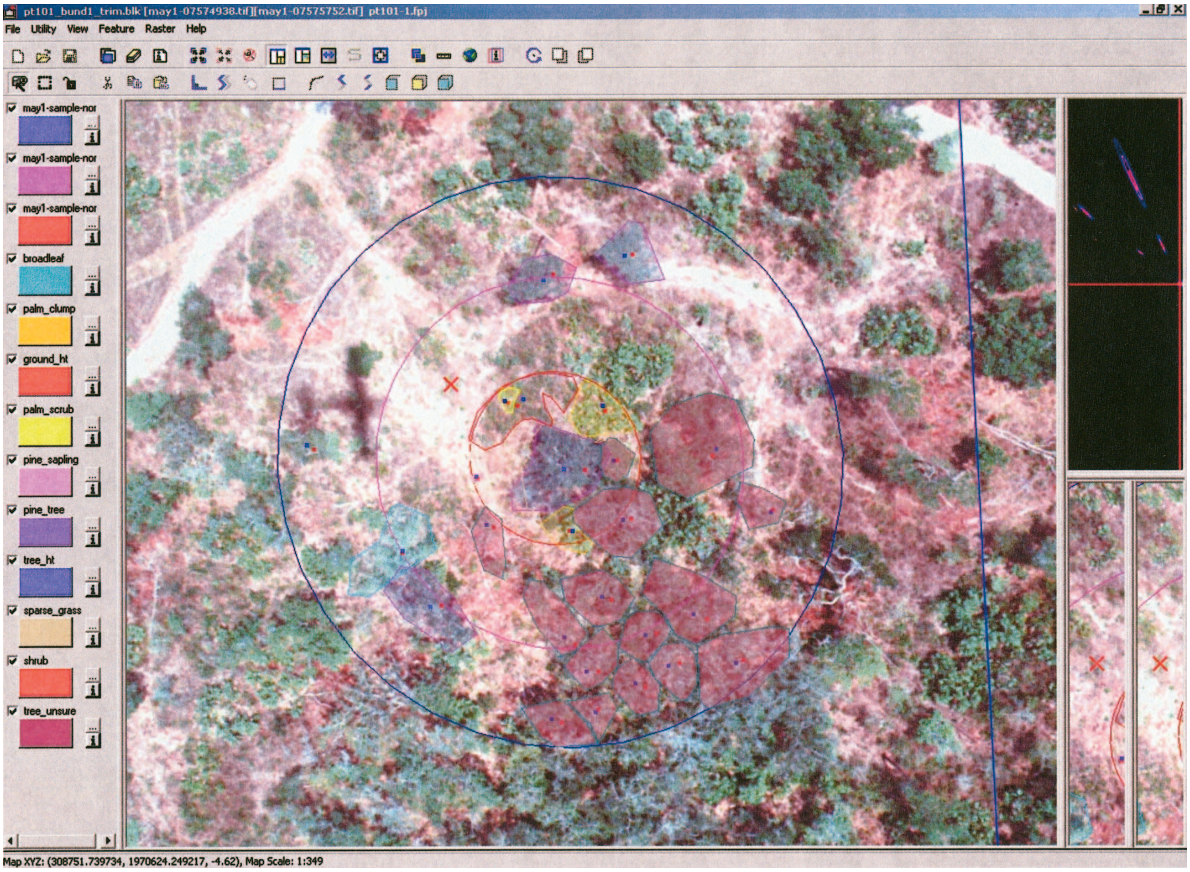

FIG. 5. A screen grab from the ERDAS-Imagine Stereo-Analyst software used to interpret the three-dimensional digital imagery. The right-hand side of the screen grab shows the two-dimensional side-by-side presentation of the two offset images used to create the three-dimensional image. The image illustrates the three nested plots (colored circles) and the digitized vegetation components within the plots of the pine savanna. Red dots represent ground measurements (registered in its accompanying crown polygon), and blue dots represent tree, shrub, or palmetto height measurement. Blue polygons are pine trees; turquoise polygons are broadleaf trees; burgundy polygons are unidentified tree species; yellow polygons are palm thickets; and red polygons are shrubs. Note the silhouette of the plane capturing the multispectral three-dimensional aerial digital imagery system (M3DADI) data.

the product of crown area and height vs. biomass carbon per tree for both groups. During the imagery analysis, we sometimes found that it was not possible to conclusively distinguish a pine from a broadleaf tree; thus, we developed a third allometric equation by combining the harvest data for the pine and broadleaf species.

For the palmetto thickets and palmetto clumps, we first expressed the harvested biomass data on a per unit area of ground basis (the 1×1 or 2×2 m^2 subplots).

TABLE 1. Details of the field data collected in 2002–2003 to create allometric equations between biomass carbon and variables measurable from the air for the main components of the pine savanna located in the Rio Bravo Conservation and Management Area, Belize.

Vegetation component	*N*†	Measurement unit	dbh range (cm)	Height range (m)	Crown area range (m^2)	Biomass range (kg)
Broadleaf trees	54	tree	5.7–52.5	2.2–17.0	1.0–200.1	1.8–1872
Pine trees	53	tree and saplings	1.0–52.4	1.0–19.1	2.8–104.8	0.04–1035
Palmetto clump	36	1 × 1 m		2.0–5.6		7.7–75.7
Palmetto thicket	40	2 × 2 m		0.8–4.6		2.4–45.8
Shrub	51	shrub		0.4–6.8	2.0–19.1	1.5–50.1
Grass	31	28 cm^2 subplot				0.04–0.36

† *N* is the number harvested.

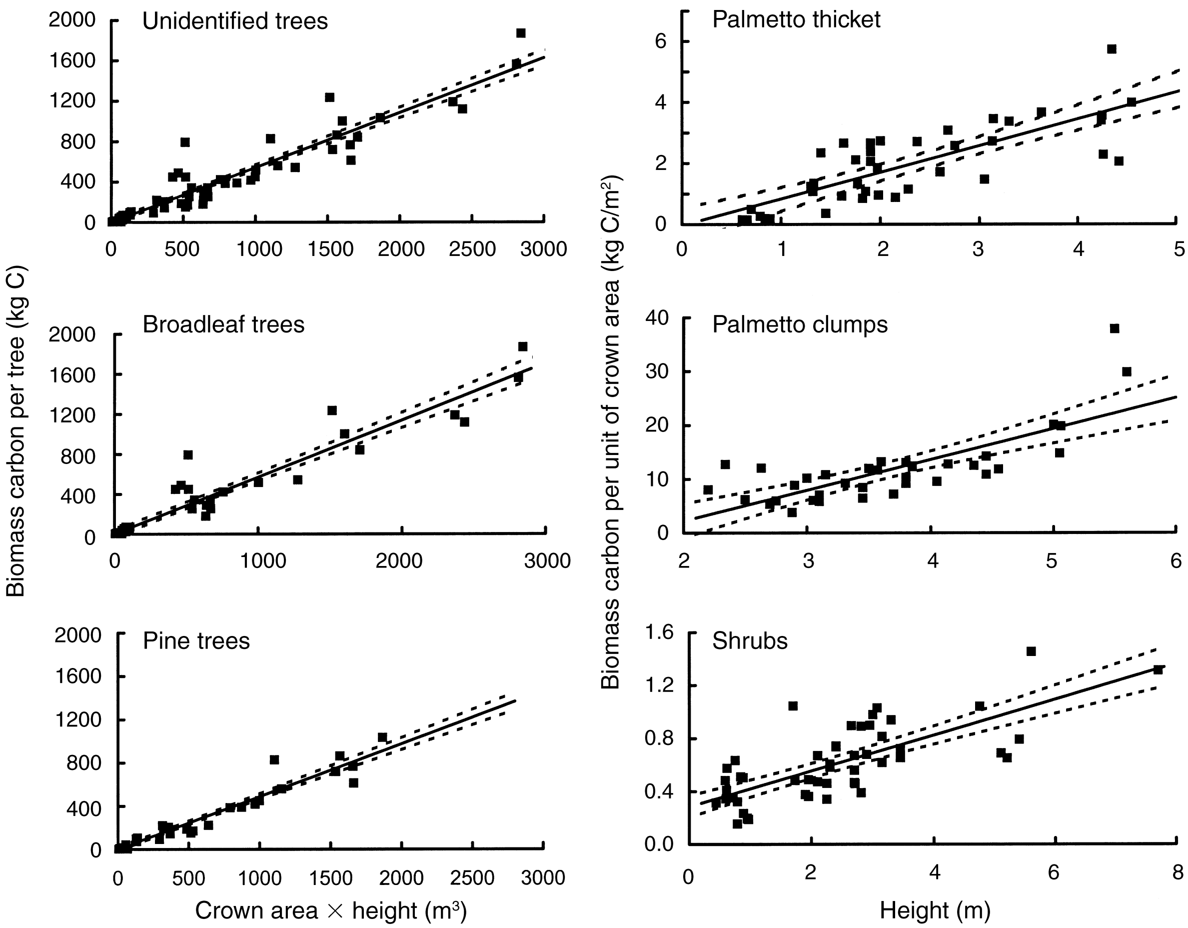

FIG. 6. Relationships between biomass carbon per tree and the product of crown area and height (left-hand panels) and between biomass carbon per unit of crown area and height (right-hand panels) for the vegetation in the pine savanna of Belize. Note that the scale for height for the palmetto clumps does not go through zero. The dotted lines for each relationship are the 95% confidence intervals.

Allometric regressions were then developed for biomass carbon per ground area (in kilograms per square meter) and mean height of the vegetation in the subplots. Shrubs were treated in a similar manner, except the harvested biomass was expressed on a per-unit-of-crown-area basis. For each shrub, the crown area was calculated as the area of an ellipse using the two crown diameter measurements. The harvested oven-dry biomass was then divided by the crown area to give an estimation of biomass carbon (in kilograms) per square meter of crown area. An allometric equation was then developed between biomass carbon per crown area (in kilograms per square meter) and mean height of the shrubs.

The allometric equations resulting from this analysis were applied to crown area or ground area and vegetation height data obtained from the analysis of the imagery to estimate biomass carbon per plot. Nested plot level biomass carbon values were extrapolated to per-hectare values using the ratio of area of a hectare to the plot area.

RESULTS

Allometric equations

The highly significant allometric equations of biomass carbon vs. height and crown area for all tree groups were linear in shape, went through the origin, and had high r^2 (Fig. 6 and Table 2). On average the biomass carbon per tree for the broadleaf species was higher than for the pine species, most likely caused by the higher wood density and more branching for the broadleaf species. However, when we combined both data sets, the resulting equation maintained its high significance and high r^2. The form of the equations for trees is very similar to those based on basal area and tree height, as might be expected. These are the first set of such equations to our knowledge.

The equations for the palmettos and shrubs were also linear but with lower r^2 than for trees (Fig. 6 and Table 2). The biomass carbon of the palmetto clumps and thickets are markedly different from one another although their height range is very similar (Fig. 6). On

TABLE 2. Allometric equations used for estimating biomass carbon (in kilograms of C) as a function of crown area (in square meters) and height (in meters) for the major components of the pine savanna.

Vegetation component	Equation	r^2
Broadleaf trees	biomass carbon = 0.57 × (crown area × height)	0.92
Pine trees	biomass carbon = 0.49 × (crown area × height)	0.95
Unidentified tree†	biomass carbon = 0.54 × (crown area × height)	0.92
Palmetto clump‡	biomass carbon = (−9.21 + (5.71 × height)) × crown area	0.58
Palmetto thicket‡	biomass carbon = (−0.038 + (0.87 × height)) × crown area	0.62
Shrub‡	biomass carbon = (0.285 + (0.135 × height)) × crown area	0.53
Sparse grass§	biomass carbon = 0.233 × area	SE = 21.2
Dense grass§	biomass carbon = 0.429 × area	SE = 25.6

† This equation was developed for use where it was not possible to distinguish between the tree species; the equation is based on the data sets for pine and broadleaf trees combined.

‡ The biomass carbon was originally expressed on a per-unit-of-crown-area basis; we have rearranged the equations to demonstrate how they were used in the calculations of carbon stocks.

§ Eleven plots were in sparse grass area, and 20 plots were in dense grass area.

average the palmetto clumps contained about 4.5 times more biomass carbon per meter of height than the palmetto thickets. Compared to the shrubs with 0.2 kg carbon per meter of height, palmetto clumps contain about 20 times as much biomass carbon per meter of height and palmetto thickets about five times as much.

Patches of dense grasses contained about twice as much biomass carbon as sparse grasses (Table 2).

Estimated carbon stocks

The mean total aboveground biomass carbon stock for the 77 plots was 13.1 Mg C/ha with a 95% confidence interval of 2.2 Mg C/ha or ±16% of the mean (Table 3). Fifty-one percent of the total carbon stock was contributed by the trees, 21% by palmettos, 4% by shrubs, and 25% by grasses.

The relationship between the total carbon stock in a plot and the contribution to the total by trees alone (both expressed on a per-hectare basis) is shown in Fig. 7. Although on average trees were present in 74% of the plots and accounted for a large proportion of the carbon stock in aboveground biomass, it is clear that in plots with low carbon stocks, palmettos, shrubs, and grasses contained significant amounts of carbon (Fig. 7). More than half of the sample plots contained <5 Mg C/ha in trees, and their total carbon stock was up to 2–10 times more than in trees.

The coefficient of variation (CV) was high for all vegetation types, reflecting the highly heterogeneous nature of the system. The CV was 71% for all components combined but 118% for trees and 303% for shrubs. By examining the mean and the standard deviation for the 77 plots studied, we estimated that 202 plots, or about 2.5 times more than already measured, would be needed to attain a targeted precision of ±10% of the mean with 95% confidence.

TABLE 3. Biomass carbon estimates from combining the allometric regression equations with the measurements from the interpreted 77 aerial imagery plots.

Plants	Biomass (Mg C/ha) Mean	SD	95% CI	Maximum	Minimum	CV (%)
Trees	6.8	8.0	1.8	40.9	0.0	117
Palmettos	2.8	4.5	1.0	23.2	0.0	163
Shrubs	0.5	1.6	0.4	12.6	0.0	303
Grass	3.1	1.0	0.2	4.5	0.0	31
Total	13.1	9.5	2.2	46.3	2.4	72

Error analysis in image interpretation

Differences in the image interpretation by two independent image analysts emerged mainly through measurements of heights and crown areas (Table 4) and occasionally were caused by differences in the classification of vegetation types. Twenty-eight trees and 12 palmettos were randomly selected for further examination. On average, crown areas measured by the two analysts differed by 22% and height measurements by 28% (Table 4). As might be expected, the error in total height measurements was higher than for crowns because the total height measurement is based on identifying two measurement points: the ground and the crown height, both of which have an error associated

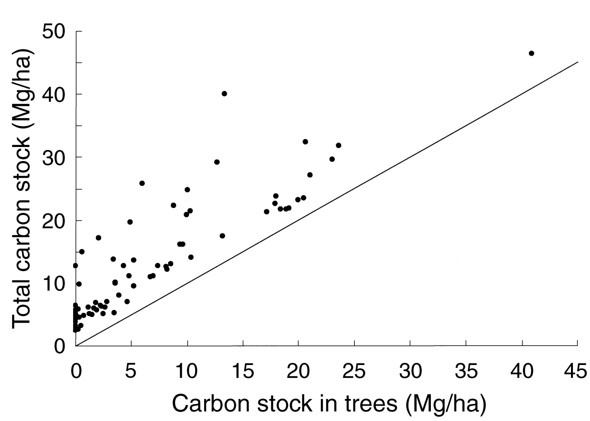

FIG. 7. Pattern of distribution of the carbon stock in the aboveground biomass of all vegetation and the carbon stock in aboveground biomass of all trees in the 77 plots of the pine savanna. The dotted line represents the situation in which all the carbon would be in trees only.

TABLE 4. Summary of measurement errors in height and crown area generated during the interpretation of the digital images.

Plants	No. measured	Height range (m)	Height difference (m)			Total height (% difference)	Area range (m^2)	Area (% difference)
			Ground	Crown	Total			
Total	40	1.0–21.8	0.75	1.44	1.70	28	1.2–103.9	22
Trees	28	2.2–21.8	0.80	1.69	2.00	17	3.3–103.9	19
Palmettos	12	1.0–3.6	0.65	0.84	1.00	51	1.2–25.3	29

Note: The data are from the seven randomly selected plots for reanalysis by a different person (see *Methods: Collection of data from the digital imagery*).

with them. The absolute error in tree height was greater than for palmetto height, whereas the absolute error in tree crown area was less than for palmetto. However, on a percentage basis, height and crown area measurements of trees were less than those for palmetto height and crown area, as might be expected given the smaller stature of the palmettos compared to trees (Table 4). Although errors did occur between the two analysts, across the seven plots examined there was no significant difference in the resultant biomass carbon estimates (ANOVA, $P = 0.201$).

DISCUSSION

The pine-savanna system in the RBCMA of Belize is an open forest with a tree canopy cover of about 10% (from summation of all tree crown areas for all plots expressed as a percentage of total plot area), with low numbers of pine trees (on average 29 trees/ha), some broadleaf species (on average 5.7 trees/ha), scattered patches of palmetto that can attain high densities in some places (up to 23 Mg C/ha), and a relatively large number of pine saplings (on average 42 saplings/ha). Most of the carbon stock is in the trees despite their low density, although the grasses account for the second largest carbon pool. The ecosystem is highly heterogeneous and to attain a 95% confidence interval of ±10% of the mean carbon stock based on sampling error only would require the analysis of at least 200 plots.

Is the M3DADI system cost effective?

For comparing the cost-effectiveness of the M3DADI approach with conventional field methods, we collected data only for the time (in person-hours) involved in each of the various steps. We focused only on the variable costs of collecting the data and performing the analyses; we assumed that the fixed costs involved would be the same for both methods. The overall goal was to compare the total person-hours needed by both approaches to collect the same set of data to achieve a 95% confidence interval of ±10% of the mean based on the sampling error only or for 202 plots.

For the M3DADI approach, the time data for collecting the imagery, processing the imagery into the three-dimensional block files, selecting the images to interpret, setting up the images with the nested plots and the GIS attribute files for 202 images, collecting the data from the images, and converting the imagery data into Excel files ready for combining with the allometric equations is estimated at 283 person-hours. For the conventional field approach, the estimated time data for establishing the same number of plots, including travel to and from the study area and between plots, collection of all field data in each plot, drying and weighing plant samples (mostly grasses from subplots), and entering the data into an Excel file for combining with allometric equations is 865 person-hours. The two sets of time data for these two approaches is the time needed to accomplish the same task: collect all data for estimating the carbon stocks in live vegetation and prepare it for the final step in the analyses.

The largest single unit of time for the M3DADI approach is the processing and preparation of the imagery ready for interpretation: it took 65 person-hours for this step but the result was the complete processing of all the transects and the preparation of all three-dimensional image block files. As the block files are prepared in just a few operations, essentially little time is saved by processing parts of the transects. The time needed for this step would not vary whether 30 or 230 plots were interpreted. In fact we found that the break-even point in person-hours was at 25 plots, where the conventional field approach was more time-efficient. However, as more than 200 plots would be needed to achieve the targeted precision for the tropical savanna, the M3DADI approach clearly has an advantage, even considering the different skill set needed by each approach. In more homogeneous ecosystems in which few plots are needed (<25) to achieve the desired precision in measurements, conventional field approaches would be more cost effective.

The cost comparison presented here is based on person-hours only, and it is expected that conversion to actual monetary costs might produce a different conclusion. For example, an airplane, with aviation gas, and pilot is needed to collect the imagery; experience has shown this to cost approximately US$300 per hour of engine time. The number of hours of flying depends on the distance between the study area and the airport, on the fuel capacity of the plane (the more fuel it can hold the longer the time in the air), and local weather conditions. Air turbulence is a critical factor in the collection of usable data and can restrict flying to a few hours in the morning for areas in warmer climates. For collecting the Belize data, it took ~8 h of flying time at a cost of approximately US$2400. Using a conventional field approach, the equivalent cost would be for a vehicle rental, usually a truck or a four-wheel drive vehicle, and given the length of time in the field to collect the data, this could run into 25–50 d depending on the size of the field personnel (a two- or four-person team). Our experience in Belize suggests a daily cost, including gas, of about US$42, for a total cost of approximately US$1000 to $2000. Labor costs will also vary, with local forestry technicians likely to be paid at a lower rate than United States-based image analysts. However, given the three-fold difference in person hours between the two methods, it is still likely that the M3DADI approach will be more cost effective.

Future refinements to the M3DADI system for application to carbon estimation

Precision represents how well a value is defined; it illustrates the error in the estimation process. The errors in estimating carbon stocks include the sampling error, the measurement error, and the model error (the allometric equations). The sampling error is generally the largest source of error and can account for up to 80–90% of the total error (Phillips et al. 2000); measuring more plots can reduce the sampling error. As noted above, to reduce the sampling error to within 10% of the mean with 95% confidence would require a total of 202 plots.

The error in field measurements is relatively low, often less than 5% for dbh and less than 10% for height (Phillips et al. 2000). The measurement error of the imagery (height and area) was relatively high, estimated to be about 29%. The large error in height measurements occurs primarily as a function of the manner in which height data are collected. Because tree height is a product of two height measurements (ground and crown height), the potential for error tends to be higher. Using shuttered glasses to correctly place the cursor at the specific elevation of an object in stereo view is an acquired skill that may take some time to develop. This process can be assisted by viewing, without glasses, a two-dimensional side-by-side presentation of the two offset images used to create the three-dimensional image and adjusting parallax until the cursor sits over the same point on each image (shown on the right-hand side of Fig. 5). However, this approach requires a distinct, yet relatively small characteristic in both images that can be used to line up the cursor. The settings for how the cursor moves up and down in the z dimension is also important. In our study, the settings were such that each click of the mouse equaled 0.5 m; it was therefore difficult to be more precise than 0.5 m.

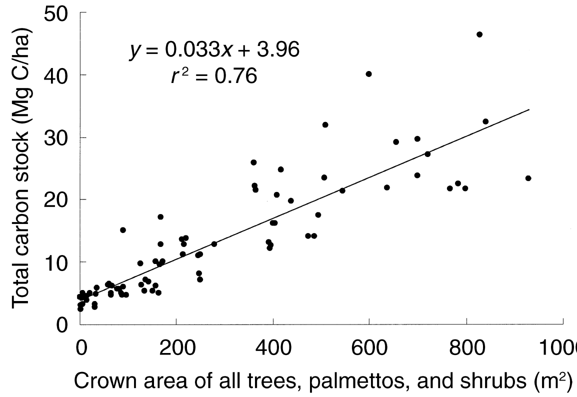

FIG. 8. Relationship between total aboveground carbon stocks and crown area per plot of all trees, palmettos, and shrubs for the pine savanna.

Another source of error in the image interpretation process comes from the misidentification of species groups. Fortunately, the classes that were most difficult to distinguish (pine trees and broadleaf trees) do not differ greatly in their allometric equation (Table 2). The error was partly a function of the nested plot design as we did not anticipate the difficulties in plant identification. If one interpreter identified a tree in the outer ring between the second and third nested plot as a broadleaf, it was not measured, but if the same tree was thought to be a pine by another interpreter, it would be measured. This led to higher or lower estimates for biomass due to vegetation classification. In future work using this imagery method, we would perform a more detailed preliminary analysis before establishing the sampling method. If it is in general difficult to distinguish between the tree types and the biomass of each class does not differ greatly, then it seems sensible to have just one class. In this study, for example, all trees could have been measured in a single tree class and in a single large plot.

The error in measuring height and identifying species groups from the imagery for future analysis of this pine-savanna ecosystem could be reduced if this step in the interpretation could be eliminated. We plotted the total carbon stock in aboveground biomass for each of the 77 plots against the total crown area for all vegetation except grasses, per plot, and obtained a highly significant relationship in which 76% of the variation in the data could be explained by the sum of the crown areas (Fig. 8). Use of such a relationship would save a lot of time and reduce errors for future monitoring. The total crown area, regardless of species, in an imagery plot could be measured at time one for the required number of plots (about 200), and the carbon stock (in megagrams per hectare) could be estimated for each plot using the relationship in Fig. 8. At time two, the same procedure could be repeated for another set of 200 plots, and the carbon stock estimated again.

The difference between them would provide an estimated change in carbon stocks with a known precision level in a time-effective manner.

Another way to reduce time is to use an alternative to manual image interpretation, such as the incorporation of automatic crown delineation routines. We are in the process of working to develop this capacity to take full advantage of the M3DADI product. Other researchers have had some success; however, their research has focused either on monocultures, even-aged conifer forests, or study areas with relatively little complexity (e.g., Pollock 1996, Brandtberg and Walter 1998, Andersen et al. 2001, Gong et al. 2002, Persson et al. 2002). To date the methods developed are still unable to give us improved, more time-efficient results than manual classification in complex tropical ecosystems.

Acknowledgments

The research reported here was supported by a Conservation Partnership Agreement between The Nature Conservancy and Winrock International (prime award DE-FC26-01NT411511 between US Department of Energy and The Nature Conservancy, Bill Stanley, PI). We thank Bill Stanley and Matt Delaney for field assistance, Scott Sweet for analysis of some of the imagery plots, Ariel E. Lugo for valuable comments on earlier drafts of the manuscript, and the comments from two anonymous reviewers.

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