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Assessing carbon stocks using indigenous peoples' field measurements in Amazonian Guyana

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ABSTRACT

Accurate estimations of carbon stocks across large tracts of tropical forests are key for participation in programs promoting avoided deforestation and carbon sequestration, such as the UN REDD+ framework. Trained local technicians can provide such data, and this, combined with satellite imagery, allows robust carbon stock estimation across vegetation classes and large areas. In the first comprehensive survey in Guyana conducted by indigenous people, ground data from 21 study sites in the Rupununi region were used to estimate above ground tree carbon density across a diversity of ecosystems and land use types. Carbon stocks varied between village sites from 1 Tg to 22.7 Tg, and these amounts were related to stem density and diameter. This variation was correlated with vegetation type across the region, with savannas holding on average 14 MgC ha^{-1} and forests 153 MgC ha^{-1}. The results indicated that previous estimates based on remotely sensed data for this area may be inaccurate (under estimations). There were also differences in carbon densities between village sites and uninhabited control areas, which are presumably driven by community use. Recruiting local technicians for field work allowed (a) large amounts of ground data to be collected for a wide region otherwise hard to access, and (b) ensured that local people were directly involved in Guyana's Low Carbon Development Strategy as part of REDD+. This is the first such comprehensive survey of carbon stocks, carbon density and vegetation types over a large area in Guyana, one of the first countries to develop such a program. The potential inclusion of forests held by indigenous peoples in REDD+ programs is a global issue: we clearly show that indigenous people are capable of assessing and monitoring carbon on their lands.

1. Introduction

The importance of trees and forests, especially tropical forests, as carbon sinks and stocks is well established, with forests globally sequestering 2.4 ± 0.4 PgC yr^{-1} by one estimate (Pan et al., 2011). Forests are under multiple development pressures, including logging, fragmentation, and clearing for agriculture. The latter is particularly critical in tropical regions, where land conversion accounted for carbon emissions of 1.3 ± 0.7 PgC yr^{-1} between 1990 and 2007 (Pan et al., 2011). In addition to development stressors, climate change itself is a key threat to forests in the Amazon basin (Malhi et al., 2008), and in order to mitigate rapid climate change, it is essential that forests are kept as intact as possible so they can continue as carbon stocks (Gibbs et al., 2007).

Recognition and understanding of the global importance of forest carbon stocks and forest ecosystem functioning has led to the development of several schemes whereby the maintenance of forest cover and carbon sequestration is remunerated, such as the UN REDD/REDD+ program (Reducing Emissions from Deforestation and forest Degradation; http://www.un-redd.org). These schemes, and others, such as national and international carbon trading programs, and voluntary payments for carbon sequestration services, require the measurement of carbon stock baselines, and subsequent monitoring and reporting of carbon pools (Cedergren, 2009), through a combination of remote sensing and ground truthing methods. To achieve support for REDD+ schemes and ensure that they fairly compensate forest stewards, it is essential that local stakeholders understand the carbon measurement process. This has been achieved through participatory approaches whereby local, trained, citizen scientists provide useful data across large areas, as has been demonstrated (Butt et al., 2013; Danielsen et al., 2013; Torres, 2014).

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Guyana was one of the first countries to submit a REDD Readiness Plan for testing national payments for carbon storage to the Forest Carbon Partnership Facility, a global partnership between national governments and other entities focussed on REDD+ (Forest Carbon Partnership Facility, 2013), and also one of the first to establish a national REDD program. The Guyana REDD+ Investment Fund (GRIF) was set up as part of Guyana's Low Carbon Development Strategy (LCDS), as a climate finance mechanism by which avoided deforestation could be compensated until an international REDD+ mechanism became operational (www.guyanareddfund.org). The fund was capitalized by the government of Norway.

In order to become part of a scheme such as REDD/REDD+, Measurement, Reporting and Verification (MRV) activities need to be coordinated and carried out by capable people on the ground, to complement remotely sensed monitoring data. This partnership approach reflects the importance placed on both the rights of indigenous people as stakeholders, and their involvement in the REDD process, by the Guyana-Norway Agreement (Cedergren, 2009; Gutman and Aguilar-Amuchastegui, 2012). Citizen science and other participatory approaches to monitoring provide an effective method of forest monitoring, and in the Guyana context Amerindian communities manage their resources, inform other community members of carbon stocks on their land, and gain insight and training in forest monitoring, which should enable an informed decision-making process with regard to opting in or out of the REDD program within the LCDS.

Project Fauna was a Guyana-based initiative developed by a team of researchers from various research institutions and local indigenous leaders to examine the connected nature of indigenous people and their environment (Fragoso et al., 2005; Luzar et al., 2011). The main goal of the project was an assessment of how biodiversity influences, and is influenced by, changes in indigenous human culture, and of how land use change affects these elements of coupled human natural systems (Luzar and Fragoso, 2013; Read et al., 2010; Luzar et al., 2011). Socioeconomic and biodiversity variables were measured on titled lands using a participatory approach. The project also measured above ground vegetation carbon to (1) address the issue of links between carbon and biodiversity and contribute to the discussion of bundled ecosystem services, and (2) advance indigenous community understanding of carbon, carbon politics and REDD+ programs, thus enabling their participation in the national discussion on carbon value and payments.

From 2007 to 2010, Project Fauna trained 335 indigenous technicians across 30 Amerindian communities in the Rupununi region (Fig. 1) to monitor wildlife populations and hunting patterns, and to describe vegetation structure. The success of this program (Luzar and Fragoso, 2013; Luzar et al., 2011; Read et al., 2010) led Project Fauna to initiate a vegetation and carbon assessment pilot study (http://www.stanford.edu/group/fragoso/), which aimed to: (1) build the scientific capacity of local communities in understanding the sources and stocks of carbon in the environment, and how to measure carbon in above ground vegetation (AGB); (2) estimate the carbon densities in distinct vegetation types and on titled lands, and; (3) compare tree carbon around villages to that in areas unused by people. Here we describe the results of the tree measurement/carbon assessment program carried out in the Rupununi region of south western Guyana, and outline the implications for the inclusion of indigenous people in monitoring their own carbon stocks in REDD+ schemes globally.

2. Methods

2.1. Study area

The Rupununi region is classed as 'moist tropical forest' by the IPCC (2003), with 2000–4000 mm yr^{-1} rainfall, and is dominated by savannas and forests (Read et al. 2010; Hammond, 2005). Ten types of vegetation were described in the study area (Cummings, 2013; Levi et al., 2013), and these were grouped into eight categories to maintain adequate sample sizes: High Forest Flooded, High Forest Upland, Ite Swamp, Low Forest Flooded, Low Forest Upland, Muri Shrub Upland, Savanna Flooded and Savanna Upland (Table 1). The 2006 Amerindian Act establishes land rights for Guyana's indigenous people (Fig. 1), who may claim title of their community lands. Indigenous communities that have received 'titled lands' have rights to forest and above ground resources within their boundaries (Cummings, 2013). Although rights to carbon stocks have not been defined, the government has acknowledged these rights by giving Amerindian communities the choice of opting in or out of enrolling their lands in Guyana's national REDD program and to receive compensation from government under a REDD+ agreement (http://www.lcds.gov.gy March 2013 report).

Of the 23 villages in the larger study (Luzar et al., 2011), members of 17 communities carried out the tree measuring work in the 20 sites: 15 'village' sites and 5 'control' sites. Records from one village were omitted, due to inexplicable tree size discrepancies between this site and both the literature and data from our study for the local forest types (see Section 4 for more detail) (Table 2; Fig. 1). Transects 4 km long were placed in a stratified random design around the villages and in five control areas identified as regions where no hunting, logging or gathering (of poles or non-timber forest products) occurs (see Levi et al., 2013). 111 transects and 604 plots of 0.01 ha were sampled overall, up to eight plots per transect (Table 2). This provided 6.04 ha of AGB (tree) data. The frequency of vegetation types varied widely by site and by region, with High Forest Upland and Low Forest Upland the most common types across the sampled plots. Ite Swamp and Savanna Flooded were the least common vegetation types (only two plots for each of these types) (Table 2).

2.2. Training and data collection

Three-day training sessions were held in three locations across the region over a two-week period (villages 6, 14, 19; Fig. 1), and comprised both classroom instruction and field demonstrations and practise. Common sampling protocols for major carbon pools were used, in line with other forest assessment projects, such as IPCC (2003), and RAINFOR (Metcalfe et al., 2009; Marthews et al., 2012): tree diameters were standardly measured in cm at breast height (1.3 m). Lianas were not included in the analysis. On average, 14 volunteers were trained at each of the three training sessions. The first part of the workshop focussed on carbon definitions, the carbon cycle and the measurement of carbon in the field. Two field workers per site sampled trees $\geqslant$10 cm DBH in the plots in their transects, and met with Project Fauna staff monthly to hand over data sheets and resolve any technical problems which might have arisen.

2.3. Data analysis

To reflect the fact that the Rupununi region covers two distinct geographic and political regions, separated by the Kanuku Mountains (Fig. 1), plot data were divided into 'north' (North Rupununi and South Pakaraimas) and 'south' (South Rupununi), based on differences in coarse vegetation types (Huber et al., 1995) and geology. The north Rupununi is dominated by continental sands and silts, the south Rupununi by younger granites and volcanic formations (Government of Guyana, 2001). Thus, in addition to the eight categories of vegetation types, and a comparison between village and control sites, we also consider differences between the north and south region (Table 2). The distinction between north and south is also important politically, as the north is inhabited by

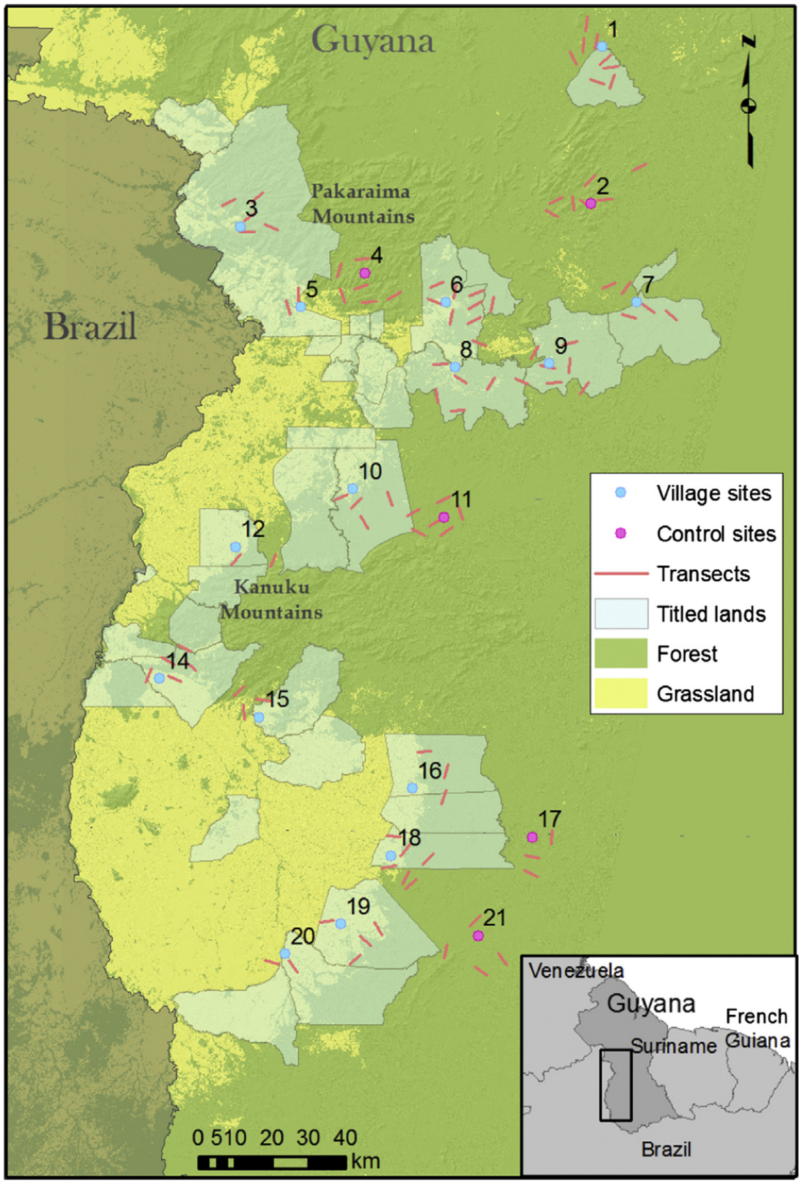

Fig. 1. Map of the Rupununi study region in Guyana, showing location of tree plot transects sampled in 2010 at 'village' and 'control' sites. The numbers refer to sites listed in Table 2. "Forest" refers to all the forest vegetation types (e.g. High Forest Upland) and "Grassland" refers to other vegetation types (e.g. Muris Shrub Upland, Savanna Upland).

Table 1
Description of vegetation types occurring along transects within the study region (meter measurement refers to tree height).

Habitat type	Description	Height (m)
High Forest Flooded	Seasonally flooded forest	20–30
High Forest Upland	Terra firme forest	20–35
Ite Swamp	*Mauritia flexuosa* palm dominated seasonal wetland	⩽20
Low Forest Flooded	Seasonally flooded forest	⩽15
Low Forest Upland	Terra firme forest	⩽15
Muri Shrub Upland	Terra firme scrub on white sand soils	⩽10
Savanna Flooded	Seasonally flooded grassland with occasional small trees	⩽5
Savanna Upland	Terra firme scrub with occasional small trees	⩽5

the Makushi people and the south by the Wapishana, whose language, cultural practices and occupation patterns differ (Luzar and Fragoso, 2013). Based on the regional rainfall regime, the allometric equation for 'moist tropical forest' was used to calculate biomass (IPCC, 2003), and multiplied by 0.5 to derive above ground tree carbon:

$$Y = 0.5 \cdot \exp[-2.289 + 2.649 \cdot \ln(\mathrm{DBH}) - 0.021 \cdot (\ln(\mathrm{DBH}))^2]$$

where Y = kg C.

Statistical analyses were carried out to compare (1) carbon densities between different vegetation types, analyzing control and village plots separately; (2) village with control plots for different vegetation types, and; (3) north and south plots by vegetation and plot type (village/control). Generalized linear models were fitted to quantify the variation of carbon density (MgC ha^{-1}, log transformed), and the importance of interactions evaluated using model selection (AIC). We used models that included plot and vegetation interaction with region as a factor, and for the interaction of plot with region (Tables 3 and 4). A logistic regression analysis was carried out to determine how carbon density varied with vegetation type.

Table 2
Number of plots of each vegetation type, per site and region ('N' = North Rupununi and South Pakaraimas, 'S' = South Rupununi), and total number of sampled transects and plots by site. The 'control' plots are underlined.

Site	High Forest Flooded	High Forest Upland	Ite Swamp	Low Forest Flooded	Low Forest Upland	Muri Shrub Upand	Savanna Flooded	Savanna Upland	Number of transects	Number of plots
1N	8	22		6	12				8	48
<u>2N</u>		31							8	31
3N		15		1	6			1	6	26
<u>4N</u>		12			15				5	27
5N		3			8			4	3	15
6N	3	8	1	6	19	3		2	8	42
7N	10	16		9	6				8	41
8N	2	13		15	13	8			7	51
9N	4	9		17	14	4			7	48
10N	2	14		3	11	1			5	31
<u>11N</u>	8	33		3	12				8	56
12N	1	5		6	9				3	21
N total	38	181	1	66	125	16	0	7	76	437
14S	3	3		1	14			6	7	27
15S		6		2				1	3	9
16S	5	12			6				3	20
<u>17S</u>	5	13							3	18
18S	1	13		1	16		2	2	6	35
19S		5			1			1	4	7
20S			1		1			3	3	5
<u>21S</u>	10	36							6	46
S total	24	88	1	4	38	0	2	13	35	167
Total	62	269	2	70	163	16	2	20	111	604
Proportion of control plots	37%	46%		4%	17%					

The data were error-checked and 'cleaned' before analysis by a scientist in the field, including cross-checking with tree size data available from another project for the same transects (Cummings, 2013). Data from this work were available for trees larger than 25 cm DBH for control and village sites in common with our dataset (12 sites in total). The DBH values did not differ significantly between the two datasets (t-test significance results ranged from $0.2 < P < 1$ for comparisons between common plots). Following this process approximately 7% of the measurements were excluded from the analyses.

2.4. Estimation of carbon biomass within village titled lands

An important part of the project's engagement with local indigenous communities was the provision of estimates, for their own use, of carbon stocks within their titled lands. The tree carbon density measurements for each vegetation type were applied to an area-wide vegetation map in order to calculate titled land carbon stocks. A land cover classification map was constructed based on the Landsat TM imageries (Path 231, Row 57 and 58) and the ground truth data (Fig. S1; Levi et al., 2013; Cummings, 2013). Titled land estimations of carbon stocks were calculated by applying the carbon density value per hectare for each vegetation type (from the plot-based calculations) to the land coverage of the Landsat vegetation classes (Tables S1 and S2). These values were then summed for the area within the border of a village's titled land.

3. Results

3.1. Above ground tree carbon

The DBH of the trees across all the sample plots ranged from 10 cm (the cut-off point) to 153.4 cm, and the mean DBH varied by vegetation type (Fig. 2). High and Low Forest Upland and Ite Swamp had the largest tree diameters, and Muri Shrub Upland and Savanna Flooded the smallest diameters. Stem density differed between control and village plots across all vegetation types (510 stems ha^{-1} and 427 stems ha^{-1}, respectively). Carbon density varied with vegetation type (logit regression: F value = 3.814, $P < 0.001$). Mean carbon per hectare ranged from 20.3 MgC ha^{-1} to 220.1 MgC ha^{-1}, for the individual sites, a function of vegetation type and type of site ('village' or 'control').

In village plots, High and Low Forest Upland (188.3 MgC ha^{-1}; 130 MgC ha^{-1}) and Flooded High and Low Forest (97.8 MgC ha^{-1}; 101.8 MgC ha^{-1}) had the highest carbon per unit area, while Savanna Flooded and Savanna Upland had the least tree carbon (4.5 MgC ha^{-1}; 28.3 MgC ha^{-1}) (Fig. 3a). Comparison of carbon density by vegetation type, for village and control plots separately, revealed significant differences between most vegetation types in village plots, while in the control plots, only High Forest Upland and Low Forest Upland differed significantly from each other (Table 3). For the four 'forest' types combined, control plots had 238.9 MgC ha^{-1}, and village plots 129.5 MgC ha^{-1}. Analyses of each vegetation type individually, comparing village and control plots, indicated that High Forest Flooded, Low Forest Flooded and Low Forest Upland differed significantly, while there was no difference for High Forest Upland between village and control plots (Table 4). Comparing 'north' and 'south', although there was a significant difference overall, and for the four forest types combined ($P < 0.001$), breaking the data down by individual vegetation type or plot type revealed no significant difference.

3.2. Above ground carbon stocks of titled lands

Carbon stocks varied significantly between titled lands, a reflection of the differences in spatial extent and vegetation types (Table 5). The village titled lands with the greatest mean tree carbon MgC ha^{-1} were 7N and 9N, and the sites with the smallest mean tree carbon per hectare were 12N and 14S (Fig. 3b). The variance clearly reflects the extent of the different vegetation types in each titled land and the differences in size of titled land area. The lowest titled land carbon estimate, for site 12N – 37 MgC ha^{-1}, derives from an area of mainly grassland (Fig. 1).

4. Discussion

This first comprehensive assessment of standing carbon stocks and vegetation types across a large region in Guyana showed the value and efficiency of using Amerindian stakeholders in REDD+ work. The implications for the LCDS and REDD+ for Guyana and indigenous people have not previously been elucidated with an underpinning of observed forest data.

4.1. Vegetation type and regional variation

The indigenous field technicians working with Project Fauna collected and provided sufficiently accurate data to enable the estimation and assessment of their carbon stocks, as reported in other studies employing participatory methods (Butt et al., 2013; Danielsen et al., 2013). The data collected by one of the 21 communities were unfortunately too problematic to be used in our analyses – the reasons remain unclear and the data were unable to be salvaged. Importantly, it was easy to detect when a problem had occurred with data quality as the diameter measurements were so different to those of other sites. Overall, >92% of the collected data were suitable to use in the analysis. In general, local technicians were motivated to be as accurate as possible as they had a vested interest in knowing how much carbon is held on their titled lands, now that it has value through the climate finance mechanism. While this is a positive step, it will be important to ensure that human bias as a result of potential conflicts of interest (i.e., reporting larger carbon stocks than actually exist through provision of erroneously large diameter measurements) should be avoided. There are several possible ways of achieving this, including multiple teams measuring in the same vegetation type; cross-checking measurements for the same site using different teams; re-measuring plots where diameter values are systematically higher than the overall mean, and; informing of potential penalties for deliberate over-estimates, such as disqualification from payment schemes.

Although Guyana does not allow independent trading of carbon by individual land title holders, it would provide pro-rated payments to villages that 'opt in' to the LCDS mechanism and sign a REDD+ agreement with government (http://www.lcds.gov.gy, March 2013 report). Knowledge of amounts and patterns of carbon content on the land would facilitate negotiation and decision making by Amerindian communities choosing to opt in or out of the national REDD program. It would also increase national and international understanding of the contribution of Amerindian titled lands to carbon stocks and carbon loss relative to other land use types in the country.

Table 3
GLM output table indicating significant differences in mean MgC ha between vegetation types, split by village and control. HFF = High Forest Flooded, HFU = High Forest Upland, LFF = Low Forest Flooded, LFU = Low Forest Upland, MSU = Muri Shrub Upland, SU = Savanna Upland, SF = Savanna Flooded. Model = glm (carbon biomass ~ plot (village/control) ∗ vegetation (type) + region (north/south) + reg:plot).

Village	HFF	HFU	LFF	LFU	MSU	SU	SF
HFF		–[**]	–[x]	–[x]	–[***]	–[***]	–[**]
HFU			–[*]	–[x]	–[***]	–[***]	–[***]
LFF				–[*]	–[***]	–[***]	–[**]
LFU					–[***]	–[***]	–[**]
MSU						–[x]	–[x]
SU							–[x]
SF							
Control	HFF	HFU	LFF	LFU			
HFF		–[x]	–[x]	–[x]			
HFU			–[*]	–[x]			
LFF				–[x]			
LFU							

[*] Significance (P) = 0.1.
[**] Significance (P) = 0.05.
[***] Significance (P) = 0.01.
[x] No statistically significant difference.

Table 4
GLM output table indicating statistically significant differences in AGB between forest types in village and control plots, and north and south (for vegetation types which occur in both north and south control plots). Vegetation type acronyms as in Table 3, carbon density values included for comparison. Model = glm (carbon biomass ~ plot (village/control) ∗ region (north/south) + vegetation (type)).

Village – control	All	n/s	Village (MgC ha^{-1})	Control (MgC ha^{-1})
HFF	–[**]	–[x]	97.8	152.8
HFU	–[x]	–[x]	188.3	167.2
LFF	–[***]		101.8	453.6[a]
LFU	–[**]		130.0	182.0

[*] Significance (P) = 0.1.
[**] Significance (P) = 0.05.
[***] Significance (P) = 0.01.
[x] No statistically significant difference.
[a] This value derives from a very small sample size.

Carbon densities varied across the eight different vegetation types found in the Rupununi forest-savanna region, as would be expected (Table 3). Differences also occurred among forest categories, for example High Forest Upland supported more carbon than both High Forest Flooded and Low Forest Flooded in village plots. This suggests that carbon stock baselines, such as for REDD and REDD+ programs, originating from generalized forest data from remote sensing, and correlated with national and international data bases, may not reflect local and regional level carbon stocks (Mitchard et al., 2014). This will have implications for measuring carbon emission changes from the baseline under carbon payment programs where inaccurate generalizations may result in incorrect values. By vegetation type in the village plots, High Forest Upland had >30% higher carbon density than Low Forest Upland per hectare, and >40% higher than both types of High and Low Forest Flooded. However, these results are confounded by the fact that human use has affected carbon stocks in titled land (see following section): human impact on local forests drives marked differences in carbon density across vegetation types, and therefore on-the-ground measurements in managed areas may be required to assess the level of biomass extraction. Differences in carbon densities between forest types is policy relevant, as it can inform both the UN/program bodies, and developing countries, on the value of investing in expensive 'Tier III' assessments (satellite imagery and ground measurements).

While the village sites differed as to the extent of dominance of each vegetation type, overall the most frequent vegetation types in the plots across the whole area were High Forest Upland – which generally includes taller trees and denser forest – and Low Forest Upland. Muri Shrub Upland was only in plots in the northern sites, while there were more upland savanna sites in the south. This variation in dominance of vegetation types from village site to village site means that carbon density also varied between villages, as a function of stem density and tree size. The size of carbon stock for each village therefore depends on the local vegetation type, which has implications for the potential contribution of the titled land to the national REDD Program, and the pro-rated compensation a village might receive once it opts into the LCDS program.

The north–south analysis showed that the northern forests had significantly higher carbon densities than the southern forests in the control plots for the four forest types combined. In addition

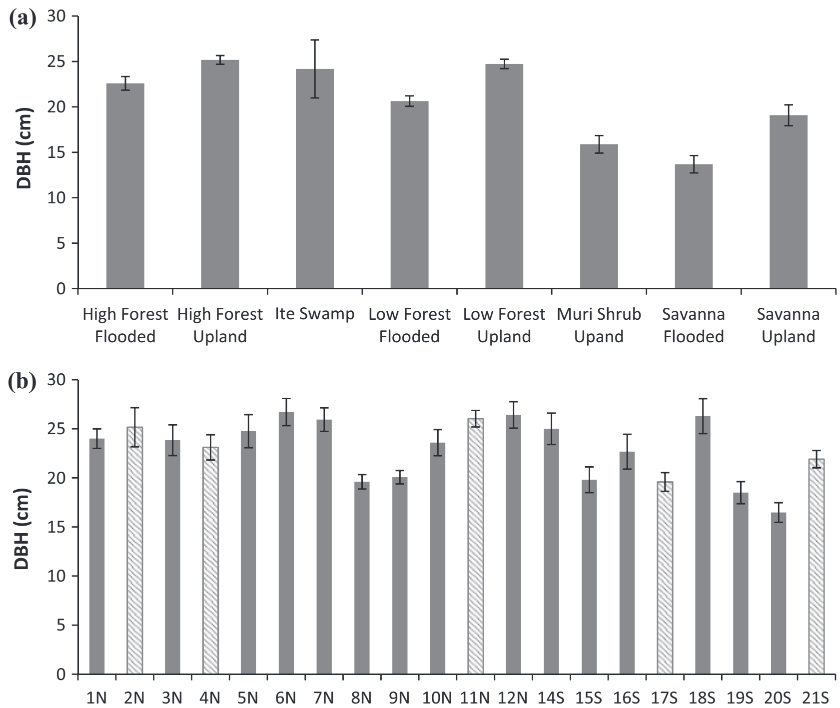

Fig. 2. Mean DBH by (a) vegetation type and (b) sample site. N = north and S = south. The control sites are represented by striped bars. Error bars represent standard error.

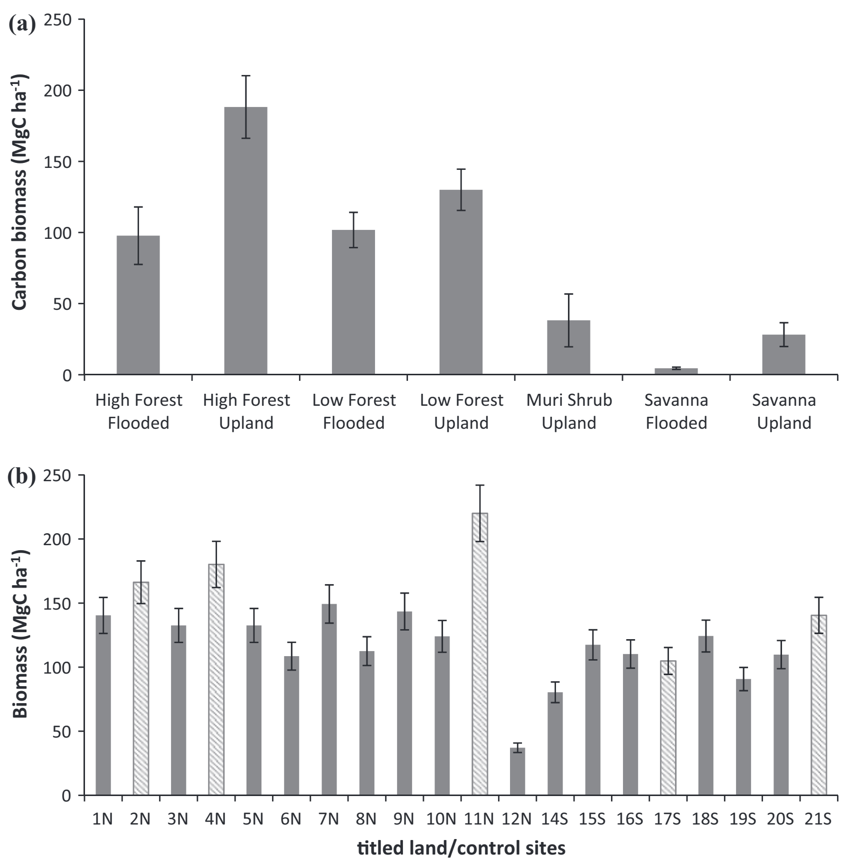

Fig. 3. Mean carbon biomass (MgC ha^{-1}) by (a) vegetation type in village plots (error bars represent standard error) and (b) by village titled land, based on satellite data. The areas encompassing control sites, included for comparison, are represented by striped bars. The error bars represent the ±10% range of uncertainty for carbon biomass estimations in (b).

Table 5
Extent, total above ground carbon stock and mean carbon density estimates of titled lands (range of uncertainty: ±10%). Titled lands 3N and 5N fall within one large communal land title. 6N also shares its titled land with other villages (not shown here).

Titled land	Area (ha)	Carbon stock (Tg C)	Average AGB (MgC ha^{-1})
1N	21,925	3.01	137.29
3N	171,275	22.71	132.59
5N	171,275	22.71	132.59
6N	61,989	6.73	108.57
7N	48,502	7.24	149.27
8N	48,586	5.47	112.58
9N	48,658	7.00	143.86
10N	54,022	6.71	124.21
12N	24,442	0.90	36.82
14S	38,287	3.08	80.44
15S	36,183	4.25	117.46
16S	42,802	4.72	110.27
18S	34,599	4.30	124.28
19S	56,416	5.12	90.75
20S	53,544	5.88	109.82

to rainfall variation between the two areas, they differ in coarse vegetation type and extent (Huber et al., 1995; ter Steege, 2001), and their geology (Government of Guyana, 2001), which drives variation in geomorphology, hydrology and soils. It is also possible that these differences reflect differences in human densities in the area before European control. These differences will affect the amount of above ground vegetation that can be supported, and thus the size of the carbon stock (Baraloto et al., 2011).

As wood density varies between tree species, different forest types, and species assemblages, can drive differences in above-ground biomass and the carbon stock estimations derived from them. Factors such as the level of inundation also influence wood density (Hawes et al., 2012; Wittmann et al., 2006), and where available, species-specific information on wood density can be included in biomass calculations to improve the accuracy of those based on diameter alone (Chave et al., 2005). The Global Wood Density Database provides wood density values for many species (Chave et al., 2009; Zanne et al., 2009; Flores and Coomes, 2011).

4.2. Human resource use impacts on carbon stocks

The control sites had higher carbon density per hectare than the village sites (for three of the vegetation types that occurred in the control sites: High Forest Flooded, and Low Forest Flooded and Upland), and greater stem density (~50%) in these sites. Although there was no significant difference in tree diameter size between the control and village sites, the large variation in stem density may reflect the impact of local forest resource use. This indicates that the carbon values for undisturbed forests should not be simply applied to forest areas of titled community lands, but rather that this difference in land use impact should be explicitly acknowledged in carbon stock evaluations. The differences in carbon biomass between control and village sites can provide information about village capacity to retain existing forest carbon and to sequester more carbon through afforestation. For undisturbed forest, there was no difference in carbon density between forest vegetation types: the differences between these and the village sites indicate that indigenous forest use has led to a significant reduction in carbon biomass near villages.

Volunteer-collected data applied to carbon density estimations have been shown to give biomass measurements accurate within a range of ±10% (Butt et al., 2013; Danielsen et al., 2013): we can state with reasonable confidence that based on measurements of trees >10 cm DBH, forests in the Rupununi region, for all village and control plots, hold between 111 MgC ha^{-1} and 136 MgC ha^{-1} on average. The northern part of the region had between 135 MgC ha^{-1} and 165 MgC ha^{-1}, and the southern part between 106 MgC ha^{-1} and 130 MgC ha^{-1}. The estimates derived from this project are in line with AGB carbon in other areas and other tropical forests globally and regionally, as derived from a combination of on-the-ground and remotely-sensed data: 126 MgC ha^{-1} (Saatchi et al., 2011). ter Steege (2001) gave an estimation of 150 MgC ha^{-1}, which included (standing) dead trees, while Conservation International (CI) estimated around 180 MgC ha^{-1} (Cedergren, 2009), and the FRA gave a South American average of 110 MgC ha^{-1} for Guyana forests (FAO, 2006). The Guyana UN REDD+ project uses Alder and van Kuijk (2009) Forestry Commission study values for their baseline estimates of forest carbon biomass (Cedergren, 2009). These were reported as tCO_2, including roots, equating to 167 MgC ha^{-1}. The large variation among carbon biomass estimates for similar forest types and regions could be the result of a number of factors, and strongly suggests the need for a standardized approach to carbon assessments.

Ours is the first forest inventory of the Rupununi region of Amazonian Guyana beyond the nine sample units surveyed from 1968 to 1973 for trees >30 cm DBH (Alder and van Kuijk, 2009), and the first to sample across savanna-forest transition landscapes, where tropical carbon stocks in general are not well established (Houghton, 2005). A comprehensive carbon density assessment from Colombia gave 112 MgC ha^{-1} for AGB (tree) in primary forest in the region, and 21 MgC ha^{-1} for secondary forest (Sierra et al., 2007), and cite lack of clear distinction between these forest types as one of the problems related to carbon stock estimation in tropical forests.

By being aware of what carbon stocks are, and how to measure them in their local areas, indigenous groups in Guyana can better participate in national and international carbon market discussions and programs, and more efficiently monitor any compensation to which they are entitled through results-based carbon payments, such as those being implemented by Norway in Guyana, and in the REDD+ programs in general. Indigenous people in Guyana believe that their participation in the national REDD program and LCDS must be informed by self-assessment of carbon stocks (North Rupununi District Development Board and the Deep South Toshao's Council, Fragoso pers. comm.), and this work provides an example of communities who have demonstrated they can effectively measure and monitor their regional carbon stocks, and thus play a key role in the ongoing LCDS and MRV activities necessary for REDD+.

4.3. Carbon biomass estimate per titled land

Applying the ground-measured carbon data to the satellite land cover classes (Table S1) enabled the estimation of carbon stocks for each of the titled land areas in the region. This provided the titled land villages and groups with detailed carbon estimates of their lands. It is crucial to engage local indigenous communities in the 'ground-truthing' of forest carbon data as they otherwise often miss the opportunity to receive their share of carbon payment due to the lack of information (Vitel et al., 2013; Jindal et al., 2008; Corbera et al., 2009). Our results revealed that there is a large variance in the average carbon density among village titled lands (Table 5), which, apart from titled land area, probably reflects the non-homogenous distribution of vegetation type. For each village area, the extent of land cover classes within the titled land was calculated from the satellite imagery (Table S2), and this gave landscape-scale information, and provided an understanding of the differences in carbon stocks between different vegetation types in their areas, and how satellite data can contribute to carbon assessments at large scales. This emphasizes the need for freely available higher-resolution remotely sensed imagery in the tropics.

4.4. Future work

Forest types need clear identification and characterization in all regions where local measurements are to be used to estimate carbon stocks. Lack of clarity can not only result in large uncertainty in carbon estimates, but may also confound comparisons with satellite imagery forest data, which are important for coherent mapping of aboveground carbon (Goetz et al., 2009).

We suggest a standard protocol for undertaking large-scale carbon stock estimates, combining satellite imagery and ground measurements, as follows: (1) use the highest-resolution satellite imagery available and establish which vegetation types can be definitively identified; (2) select multiple (GPS) locations in each vegetation type and assess its carbon density with tree measurements. This would provide a carbon value and range for each forest type identifiable on highest resolution satellite imagery, which can then be applied to any area of forest or titled land. This method, by establishing whether forest types differ significantly in terms of carbon density, would determine whether or not this level of satellite imagery would need to be used in all assessments. The level of accuracy of lower-resolution (cheaper) satellite imagery for vegetation type identification can be tested using the results from (2), and thus establish the level of detail the lower-resolution imagery can provide (it may not be able to distinguish between all vegetation types). Where different vegetation types have the same per hectare carbon, it will not be necessary to distinguish between them and thus lower-resolution imagery could be used to assess carbon stocks. This approach addresses uncertainty in our knowledge of carbon levels in different vegetation types, providing accurate data that can usefully inform programs such as REDD+ on equitable price per hectare.

5. Conclusion

We distinguish between three types of uncertainty/variation associated with carbon biomass assessments: (1) differences between forest/vegetation types in different areas; (2) differences between managed and unmanaged forest and; (3) measurement error. These factors will influence remuneration levels and the first two should be incorporated into payment calculations. Effective training and management of local field technicians is crucial to reduce measurement error and should be included in baseline-setting MRV schemes. The field work and analysis carried out in the Rupununi region demonstrates that on-the-ground forest measurements done by well-trained local workers can make valuable contributions to carbon stock estimation across large areas.

The results and findings of this project are of global importance, for example with regard to the potential inclusion of forests on land held by indigenous peoples in REDD+ programs. These programs are bilateral or international in nature, while it is unclear who owns the carbon on indigenous lands. As we demonstrate here, indigenous people are capable of assessing and monitoring carbon on their lands, and should therefore be partners in REDD+, and similar, schemes.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2014.11.014.

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SUPPORTING INFORMATION
for
ASSESSING CARBON STOCKS USING INDIGENOUS PEOPLES' FIELD MEASUREMENTS IN AMAZONIAN GUYANA

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Calculation of carbon biomass for the titled land areas by applying field observation data to remotely sensed imagery

We used the carbon dataset at each site and the vegetation classification map to calculate the carbon biomass per village titled land. The vegetation classification map was developed based on the remotely sensed images from Landsat TM (Path 231, Row 57 and 58). As the vegetation classes used for our plot survey (Table 1 in the paper) were slightly different to the land cover classes (Table S1), we calculated the average carbon biomass for each of the land cover classes, and then applied these land cover type average carbon biomass estimates to the extent of the land cover classes in every titled land (Table S2).

Average carbon biomass per hectare for each vegetation class were calculated for northern villages and southern villages from the plot values, including those from control sites (Table S1). The carbon values were calculated separately for northern and southern villages because the landscape and vegetation are distinctively different – most southern villages are predominantly located in flooded grassland (Hammond, 2005). Hectare values for each of the 12 vegetation classes in each titled land area were derived from raster cell counts at a resolution of 30 m by 30 m with ESRI ArcGIS 10.0 and aggregated to ha (Table S2). Cloud cover was included in the remotely sensed imagery (as is inevitable in this tropical region), and we therefore assumed that the same land cover matrix of a village was found under the cloud cover: the area-weighted average carbon biomass across different land cover types of each village was thus applied to these areas. We calculated the average carbon storage per titled land area by dividing the sum of carbon storage for all the classes by the total extent of the titled lands.

Table S1: Land cover classes and corresponding vegetation classes

Class ID	Land cover class description	Corresponding vegetation cover (from Table 1 in the main text)	North ($MgC\ ha^{-1}$)	South ($MgC\ ha^{-1}$)
0	Clouds, Cloud shadows and forest shadows – this will be adjusted according to local veg type means	-	0.00	0.00
1	Seasonally flooded mixed high and low forest and Muri Shrub	Low Forest Flooded + High Forest Flooded	123.73	107.30
2	Rivers, creeks, open water, flooded savanna	-	0.00	0.00
3	Seasonally Flooded and Swampy Savanna	Savanna Flooded	4.54	4.54
4	Lowland High Bush (Lowland Forest)	High Forest Flooded	186.1	165.88
5	Savanna with Bare Soil (including roads)	Savanna Upland	14.63	35.51
6	Lowland mixed high and low forest	Low Forest Upland + High Forest Upland	164.73	146.61
7	Upland savanna	Savanna Upland	14.63	35.51
8	Upland high forest	High Forest Upland	186.1	165.88
9	Upland low forest	Low Forest Upland	143.37	127.35
10	Mountain savanna	Savanna Upland	14.63	35.51
11	Mountain mixed high and low forest	Low Forest Upland + High Forest Upland	164.73	146.61

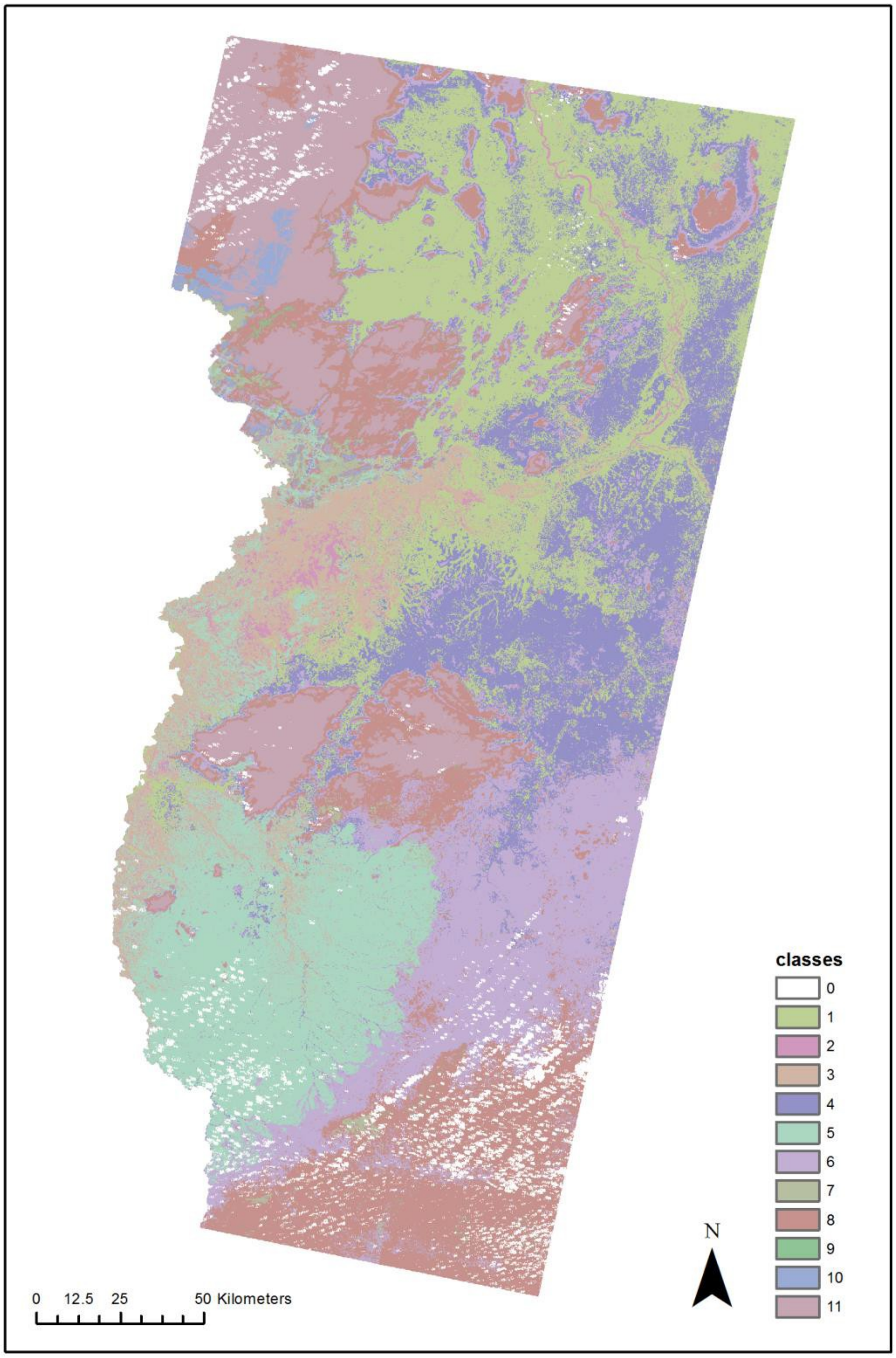

Figure S1. Land cover classification map based on Landsat TM imageries for the Rupununi region. Legend class numbers correspond with land cover descriptions in Table S1.

Table S2: The extent of land cover classes within a village's titled-land (ha)

Site	Class 0	Class1	Class2	Class3	Class4	Class5	Class6	Class7	Class8	Class9	Class10	Class11
1N	514	15225	97	19	5687	1	325	0	56	1	0	0
3N	77	2016	483	5037	2671	10835	6763	16982	46233	4437	8711	67029
5N	77	2016	483	5037	2671	10835	6763	16982	46233	4437	8711	67029
6N	0	30213	1655	13249	11292	690	3440	53	1266	129	1	0
7N	0	24386	856	381	21344	16	1465	0	49	0	0	5
8N	0	34071	792	6979	6163	148	328	8	94	1	0	4
9N	0	23334	898	2179	19849	71	1873	7	422	7	0	17
10N	0	18405	2109	8939	22764	998	728	11	64	4	0	0
12N	0	2170	2446	9364	1974	7775	675	18	18	1	0	0
14S	761	3387	773	6715	1858	12202	2280	233	3487	152	21	6417
15S	408	2434	309	2755	4484	4863	4029	1941	10273	343	296	4048
16S	0	285	49	39	2664	12503	24398	1851	952	2	53	5
18S	523	49	3	30	256	6078	26354	806	476	3	20	0
19S	580	132	55	181	901	27298	22026	1220	3956	13	48	6
20S	2937	20	6	52	626	17429	27180	202	5039	24	24	6

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