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Baseline assessment for environmental services payments from satellite imagery: A case study from Costa Rica and Mexico

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Abstract

In this study we evaluate the accuracy of four global and regional forest cover assessments (MODIS, IGBP, GLC2000, PROARCA) as tools for baseline estimation. We conduct this research at the national scale for Costa Rica and for two tropical dry forest study sites in Costa Rica (Santa Rosa) and Mexico (Chamela-Cuixmala). We found that at the national level, the total forest cover accuracy of the four land cover maps was inflated due to an overestimation of forest in areas with an evergreen canopy. However, the four maps greatly underestimated the extent of the deciduous forest (dry forest); an ecosystem that faces high deforestation pressure and poses complications to the mapping of its extent from remotely sensed data. For the tropical dry forest sites, all maps have low forest cover accuracies (mean for Santa Rosa: 27%; mean for Chamela-Cuixmala: 56%). This has implications for policy implementation.

Keywords: Carbon; Chamela-Cuximala; Costa Rica; Forest cover; Global land cover; Mexico; Payments for environmental services; Santa Rosa; Tropical dry forest; Tropical wet forest

1. Introduction

The implications of global climate change due to an increasing build-up of anthropogenic greenhouse gasses (GHG) such as carbon dioxide (CO_2) in the atmosphere have become internationally important issues (Choi, 2005; Gerlagh and van der Zwann, 2006; IPCCC, 2005; Lenton, 2006; Litynski et al., 2006) The Kyoto Protocol was proposed as potential means to mitigate climate change (United Nations, 1997). Each country listed in Annex B of the Protocol is allocated an "assigned amount of emission reduction units" (AAUs) that correspond to the nations' allowable GHG emissions (Choi, 2005; United Nations, 1997). Annex B countries include developed countries and countries with transitional economies. The AAUs are a country's baseline emission minus the percentage of emission reductions that are required by the Protocol (Choi, 2005). While most countries are required to reduce their emissions, a few such as Iceland are permitted an increase (United Nations, 1997).

Specific mechanisms are permitted under the Kyoto Protocol to help parties attain their GHG emission reduction targets; joint implementation (JI) and the Clean Development Mechanism (CDM)(Choi, 2005; Olschewski and Benitez, 2005; Pfaff et al., 2000; UNFCCC, 2003b). The JI and CDM mechanisms are project-based where an Annex B country can earn emission reduction credits by participating in a project that helps another country reduce its GHG emissions (e.g. reforestation). The difference between the JI and CDM is that JI projects are between Annex B countries whereas in CDM projects Annex B countries receive certified emission reduction units (CERs) by collaborating with non-Annex B countries (Choi, 2005; Olschewski and Benitez, 2005; UNFCCC, 2003b). Annex B countries may engage in either JI or CDM projects to help another Annex B or non-Annex B country and use the credits for their own compliance (Subak, 2000). Anthropogenic land-based activities—"land-use, land-use change and forestry" (LULUCF) are a means of achieving

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compliance to the Protocol (UNFCCC, 2001b, 2003a, b). While a part of the CDM, LULUCF activities are limited to afforestation and reforestation projects. Also, during the first commitment period, the credits resulting from LULUCF projects are capped at 1% of the base year emissions times five (Choi, 2005; UNFCCC, 2003b). Nevertheless, such activities do form part of the initiatives taken by Annex B countries. An example of a recent project in the tropics is the investment of US$2 million by the Government of Norway into Costa Rica's Private Forestry Project in exchange for 230 kt of carbon offsets (US$10/t/C) (Subak, 2000).

To evaluate the effectiveness of mitigation projects in the forestry sector and the clear definition of solid baselines, three fundamental questions must be addressed: *what is the initial extent of the forests?, what type of forest is there (primary, secondary)? what is the rate of change of the forest extent?* Estimates of payments for environmental services are greatly dependent upon the differences between the baseline and mitigation scenarios and on deforestation rates before and after the implementation of a project; the greater the difference the greater the estimate of carbon sequestration/value of environmental services (Busch et al., 2000). Therefore, it is imperative that the initial state and extent of the forest (baseline determination) be characterized as accurately as possible, a problem that is not trivial due to the lack of standardized mechanisms that can provide accurate information for different types of forests especially in the tropics (Foster et al., 2002; Subak, 2000).

While CDM projects can take place in any ecosystem, in this study we focus on tropical forests because of their importance in carbon sequestration, their general overall threatened status and the complications that arise when mapping their extent from remotely sensed data (Sánchez-Azofeifa et al., 2001). To accurately assess land cover changes in tropical environments at reasonable costs requires remote sensing technology (Subak, 2000). However, an initial problem in accurate estimation of forest cover is one of nomenclature (Jung et al., 2006). While there are numerous definitions of what is a forest (see (ITTO, 2002) for an in depth review), there is no general consensus (Jung et al., 2006). In addition, many definitions are biased towards mature wet or rain forests, neglecting seasonally deciduous forests and stages of vegetation succession (i.e. secondary forests) (Sánchez-Azofeifa et al., 2005a, b). Attempts have been made to consolidate definitions during the Marrakesh Accords (UNFCCC, 2001a, 2003a). Based on those accords "forest" is defined as "*a minimum area of land of* 0.05–1.0 *ha with tree crown cover, or equivalent stocking level, of more than* 10–30% *and containing trees with the potential to reach a minimum height of* 2–5 *m at maturity*". This is also the definition adopted by the Eleventh Conference of the Parties when discussing the implementation of CERs (UNFCCC, 2003b). In addition, stands temporarily below the thresholds but which are expected to grow or revert to forest are also included in the forest category (UNFCCC, 2001a, 2003b). However, the definition of "forest" adopted by any one country is optional within the stated minimum levels defined by the Marrakesh Accords. In this study we adopt the Marrakesh Accord's definition of "forest" and more precisely the following refinement describing the environment where dry forests are found: an *area with a vegetation type dominated by deciduous trees located in an area with a mean temperature* $>25\,^{\circ}C$*, a total annual precipitation range of* 700–2000 *mm and three or more dry months* (*precipitation* <100 *mm*) (Sánchez-Azofeifa et al., 2005b).

Methods for using remote sensing to monitor and detect tropical deforestation in the humid tropics have been successfully developed, tested and applied ((Sánchez-Azofeifa et al., 2001; Skole and Tucker, 1993; Stone and Lefebvre, 1998; Zhang et al., 2005) among many others), providing important information on the extent of tropical evergreen forests. Tropical dry deciduous forests (T-df), however, have received less attention and thus the development of remote sensing methods for quantifying the extent of the T-df has been neglected in comparison to wet/rain forests (Arroyo-Mora et al., 2005b). Significant errors have resulted from mapping the extent of the tropical dry forest from satellite images because the cloud free images are most easily acquired during the dry season when an increased percentage of the canopy is leafless, lacking the spectral signature of green leaf biomass (Arroyo-Mora et al., 2005a; Asner, 1998; Kalacska et al., 2007). This property of the canopy induces the misinterpretation of forested areas in the image for pastures or areas with dispersed trees (Pfaff et al., 2000).

Our study investigates the implications of using various global remote sensing derived land cover classification data sets of forest cover as a baseline scenario at the national level for Costa Rica. We use Costa Rica as an example for several reasons. Firstly, it has a multitude of forest types (from dry forest to rain forest) and also has a considerable history in payment of environmental services. In addition, a substantial database of remotely sensed imagery both satellite and airborne have been acquired for the entire country, including multi and hyperspectral images and aerial photograph that cannot be matched by any other tropical or sub-tropical country. Significant efforts have been made by the Costa Rican Centre for High Technology (CENAT- El Centro Nacional de Alta Tecnologia) and its National Airborne and Remote Sensing Program (El Programa Nacional de Investigaciones Aerotransportadas y Sensores Remotos) to ensure continual collection of remotely sensed data for the country. Finally, substantial efforts have been in the country through the national ministry of environment (MINAE), NGOs such as FONAFIFO and several provincial agencies such as FUNDECOR to manage and inventory the nation's forests. Costa Rica has the largest proportion of national territory in protected areas (national parks, absolute reserves, biological reserves) of any Central American country. Subsequently, we focus specifically on the dry forest in two protected areas located in Costa Rica and

Mexico and assess how the different interpretations of the global land cover classifications affect the quantification of the value associated with environmental services in the dry forest. In terms the tropical dry forest in Central America, Costa Rica and Mexico have the largest most thoroughly inventoried areas remaining, as well as under protection in terms of biological reserves or national parks.

2. Methods

2.1. Study areas

Our study is conducted at two levels: first, at the national level for Costa Rica (total area of 51 000 km^2) and second at a specific ecosystem level (tropical dry forest) for two study sites. Because of the central mountain range, the country encompasses numerous physiognomically different tropical forest types (Holdridge et al., 1971). However, to facilitate the interpretation of the results and to be consistent with forest types reliably detectable from imagery we refer to two distinct forest types: predominantly evergreen (e.g. tropical wet) and predominantly dry season deciduous (e.g. tropical dry) forest types. Subsequently, in a more detailed analysis, the two tropical dry forest areas we examine in greater detail are the Santa Rosa National Park in Costa Rica (10°48′53″N, 85°36′54″W) and the Chamela-Cuixmala Biosphere Reserve in Mexico (19°22′–19°39′N, 104°56′–105°10′W).

Santa Rosa National Park is composed of a mixture of secondary forest in various stages of regeneration (Arroyo-Mora et al., 2005a; Janzen, 2000; Kalácska et al., 2004). We refer to four stages of succession in Santa Rosa: pasture SR-P, early SR-E, intermediate SR-I and late SR-L (Table 1). The total study area for Santa Rosa is 500 km^2. The Chamela-Cuixmala Biosphere Reserve is comprised of approximately 126 km^2 of forest, the majority of which has been undisturbed for hundreds of years (Maass et al., 1982). We refer to four physiognomically different forest types in and around the biological station. Upper ridge-top and slope (CH-U) and Lower Riparian (CH-L) forest classes are mature undisturbed forests, intermediate (CH-I) is a secondary forest stage and early (CH-E) is the first stage of regeneration populated entirely by low *Acacia* sp. bushes (Table 1) (Kalácska et al., 2005). We included a buffer of 30 km around the station for the analyses, in order to include land cover types other than forest in the study area. The total study area (including the buffer zone) for Chamela-Cuixmala is 2465 km^2. In Santa Rosa there are 6 months of little to no precipitation (December–May) and a total yearly precipitation that is highly variable (915–2558 mm)(Janzen, 1993). In Chamela, the precipitation ranges from 374 to 897 mm with 80% falling between July and October (Maass et al., 1982). Drought deciduousness is the general leaf phenological response to the dry season (Gentry, 1995; Lobo et al., 2003). Gentry (1995) estimates that approximately 40–60% of the species in Santa Rosa are deciduous compared to over 80% in Chamela.

2.2. Total aboveground biomass

Of the many direct methods currently available to estimate total above ground biomass, allometric equations are probably one of the most broadly used (Brown, 2002). Site-specific regression equations have been developed to estimate plant biomass from values of diameter at breast height (DBH), height and wood specific gravity (Maass et al., 2002). In other studies, general regression equations have been developed for specific forest types from DBH. Carbon is assumed to be approximately 50% of the biomass (Brown, 2002). The most complete estimates of carbon include not only standing live vegetation but also dead wood, root biomass and soil carbon. From forest structure data we calculated total live aboveground biomass from Brown (1997) for stems above 2.5 cm DBH:

$$\mathrm{ATB} = \exp(-1.996 + 2.32(\ln D)), \quad (1)$$

where biomass is expressed in kilograms of dry mass and D is DBH in centimetres. Root biomass was estimated from

Table 1
Forest structure characteristics and allometric carbon (C) content from live total aboveground and root biomass for all stages of forest in Santa Rosa and Chamela

Forest stage[a]	Canopy height (m)	Basal area (m^2/ha)	Stem density (No./0.1 ha)	Species density (No./0.1 ha)	No. strata	C (tons/ha)
SR-P	2±0.5	0±0.0	0±0	1±0	0	—
SR-E	7.5±2.2	11.7±5.4	112±64	15±7	1	31.8±1.8
SR-I	10.3±3.4	21.4±6.8	130±35	29±5	1	60.9±2.5
SR-L	15.0±2.2	30.1±6.5	107±42	29±7	2	88.9±2.0
CH-E	1.3±0.4	0±0.0	0±0	1±0	0	—
CH-I	11.0±2.2	10.4±4.7	146±103	8±6	1	22.4±2.3
CH-U	8.9±1.8	13.2±2.5	181±5	31±12	1	29.5±3.0
CH-L	21.1±1.0	25.8±2.6	124±10	31±4	2	72.6±3.4

[a]Forest structure data for Santa Rosa are from Kalacska et al. (2004) and Arroyo-Mora et al. (2005) and from Kalacska et al. (2005.) for Chamela. Census includes only woody stems with a DBH ⩾ 5 cm.Canopy height for SR-P reflects height of African grass *Hyparrhenia rufa* (Jaragua) during the wet season. For CH-E it reflects the height of the *Acacia* sp. bushes.

Cairns et al. (1997):

$$RB = \exp(-1.0587 + 0.8836(\ln ATB)), \quad (2)$$

where ATB is aboveground tree biomass (Mg/ha). In all our estimates we include only live ATB and root biomass because we do not have data regarding dead wood or soil carbon for the study sites. In total, 26 plots of 20×50 m were sampled in Santa Rosa where stems $\geqslant 5$ cm DBH were identified and measured (Arroyo-Mora et al., 2005a; Kalácska et al., 2004). Thirteen plots of the same dimensions were included in the census in Chamela-Cuixmala (Kalácska et al., 2005) (Table 1).

2.3. Total forest cover assessment

For Costa Rica a supervised classification map (CR2000) was produced by a combination of 14 Landsat Thematic Mapper 5 and 7 images acquired in 1997 and 2000 using NASA pathfinder methodologies with a minimum mapping unit of 0.03 km^2 (Sánchez-Azofeifa et al., 2001; Zhang et al., 2005). The overall accuracy of the CR2000 data set (forest/non-forest) was estimated to be 90–92%. For the accuracy assessment, a total of 800 control points for forest with a minimum area of 0.03 km^2 were chosen and assessed on the ground (Sánchez-Azofeifa et al., 2001). The evaluation of the accuracy of the forest cover data set with the extensive collection of ground control points provide greater confidence in this data set in comparison to continental or global algorithms. This data set, resampled to 1 km^2 resolution (in order to have the same pixel size as the land cover maps), was used as the control in all analyses for Costa Rica.

For the Costa Rican national level baseline and the dry forest study sites' baseline determination analysis we examine three published and readily available global land cover maps created from different sensors: the Global Land Cover, 2000 (GLC2000) generated by the Canada Centre for Remote Sensing using SPOTVEG imagery (22 classes) using regionally defined classifications (Latifovic and Olthof, 2004), IGBP from the International Geosphere Biosphere Program created with AHVRR imagery (17 classes) (Loveland et al., 2000) and MODIS Land Cover data produced by Boston University (17 classes)(Muchoney et al., 2000). In addition, we include a regional land cover map for Central America produced by the Center for International Earth Science Information Network (CIESIN) at Columbia University under the Proyecto Ambiental Regional de Centroamerica (PROARCA). This regional land cover map was created from AVHRR imagery (17 classes)(Central American Commission on Environment and Development, 1998). All the above data sets have a spatial resolution of 1 km^2. PROARCA data are not available for the dry forest site in Chamela-Cuixmala Mexico.

Comparison of all coarse resolution maps was performed using the Costa Rica 2000 (CR2000) database. Accuracy at the national level and the specific dry forest study sites was estimated from sets of randomly generated control points extracted from the CR2000 data set. As the control data for Chamela-Cuixmala Mexico we used a supervised classification map (MX2002) generated using ASTER imagery (resampled to 1 km^2 resolution) for the year 2002 (Sanchez-Azofeifa and Quesada, unpublished).

3. Results

3.1. Forest cover estimation at the national level for Costa Rica

The overall forest cover estimates for Costa Rica from the different land cover maps are shown in Fig. 1. In comparison to the CR2000 data, each land cover map underestimates the actual forest cover for the predominantly deciduous (dry) ecosystem (Fig. 1f). The area demarcated as "dry" in Fig. 1f is predominantly deciduous or contains trees that are deciduous during the dry season (periods of little to no rainfall). This area encompasses 14% of Costa Rica (7140 km^2). The forest extent of the evergreen vegetation (Fig. 1f) however, in general, compares well between the land cover maps and the CR2000 data set except for the overestimation of the forest in the northeastern and central sectors of the country most likely due to the inclusion of palm, coffee, pineapple, yucca and other plantations in the forest cover class.

The overall forest accuracies for GLC2000 (74%) and MODIS (76%) (Table 2) reflect the high prevalence and accuracy of "forest" for the majority of the evergreen forest areas in the country (Fig. 1) (e.g. 79%—GLC2000 and 88%—MODIS) (Table 2). However, the low non-forest accuracies (e.g. 32% and 16% for GLC2000 and MODIS, respectively) for all land cover maps indicate an overestimation of the forest in the evergreen forest areas (Table 2). The poor accuracies of all data sets for the predominantly deciduous forest areas (36% mean accuracy for all data sets) indicate a severe underestimation of the deciduous forest (Table 2).

Table 3 indicates the total forest area from the land cover maps in comparison to the CR2000 data set. The total forest area estimated for Costa Rica by Mayaux et al. (1998) is also included in Table 3. Every land cover map derived from coarse resolution sensors used in this study overestimates the extent of the forest for Costa Rica by as much as 16 000 km^2 with the exception of Mayaux et al. (1998) who underestimate the forest cover by 9777 km^2. PROARCA is the closest in the overall estimate for forest area for the country with 27 792 km^2 which is only 4565 km^2 more than the CR2000 data set. The MODIS land cover data set is the farthest from CR2000 at 39 409 km^2.

3.2. Tropical dry forest sites

The total forest area from the CR2000 data set for Santa Rosa is 276.6 km^2. For Chamela-Cuixmala the MX2002 data set reveals 1925.6 km^2 of forest as control. The range

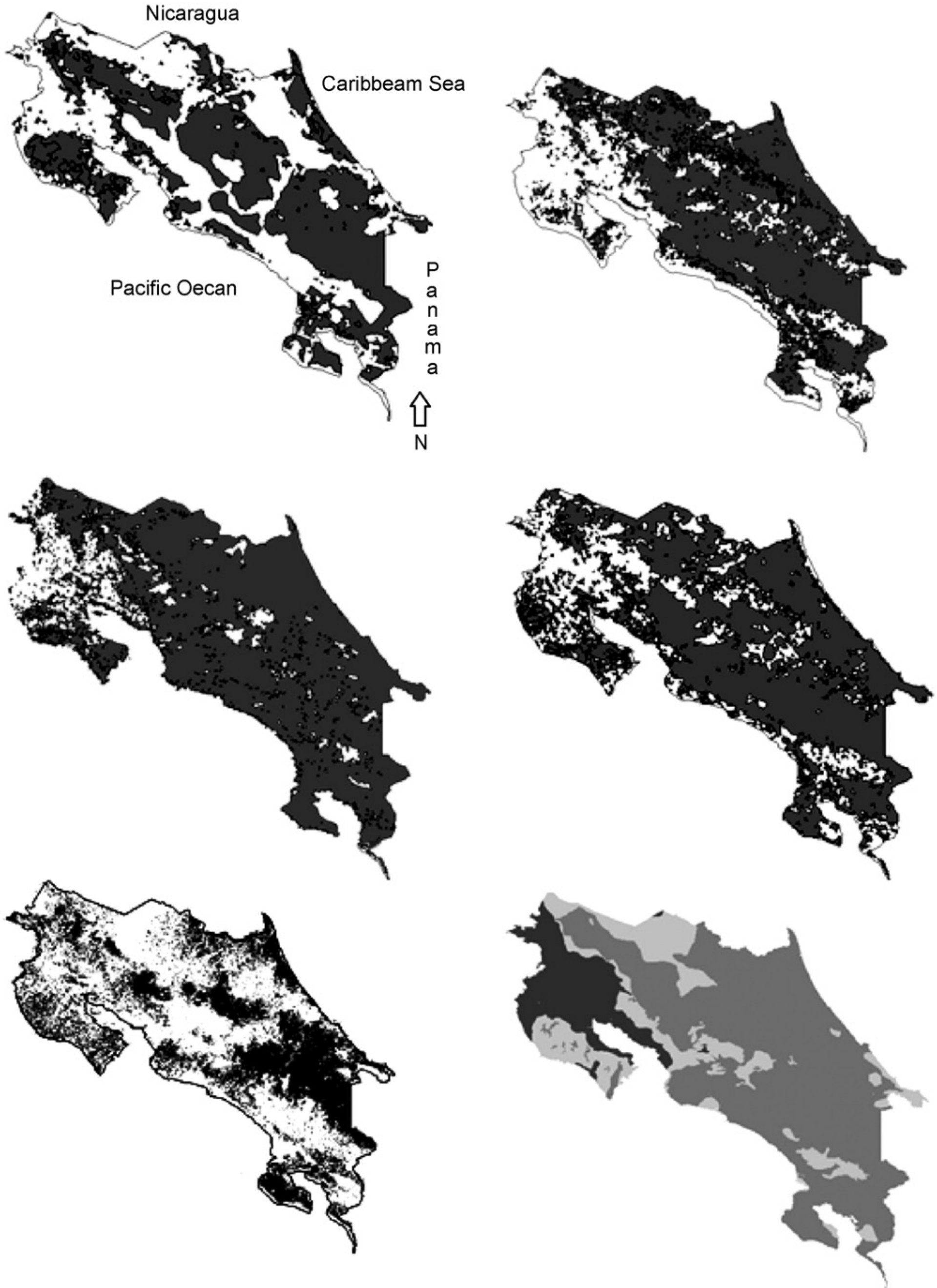

Fig. 1. Total forest cover extracted for Costa Rica from the various global/regional land cover maps. (a) PROARCA (b) IGBP (c) MODIS (d) GLC2000 (e) CR2000 (f) areas comprised of a predominantly dry season deciduous canopy (dark grey tone) and areas with a predominantly evergreen canopy (medium grey tone) in Costa Rica. Deciduous and evergreen areas were determined based on the Holdridge life zone database for Costa Rica.

of land cover classes found in the deciduous study areas based on the four global/regional land cover data sets is illustrated in Table 4. The consensus for the dominant class in Santa Rosa from the land cover maps is "cropland" or "agriculture", with the forest classes being minimal in comparison. However, from the CR2000 data for Santa Rosa, the dominant class is "forest" with an actual coverage of 55%. The actual forest cover for Santa Rosa has also been reported by an independent study from Arroyo-Mora et al. (2005b). Every land cover map derived from coarse resolution sensors underestimated the total forest in Santa Rosa by 130.6 km^2(MODIS) to 196.8 km^2 (PROARCA) in comparison to CR2000. The highest accuracy is from both the PROARCA and MODIS data

Table 2
Forest and non-forest accuracies (%) from the national level analysis for Costa Rica and the two tropical dry forest sites (Santa Rosa and Chamela-Cuixmala)

Analysis level and thematic class	GLC2000	MODIS	IGBP	PROARCA	Mean
Costa Rica predominantly deciduous	56	35	18	36	36
Costa Rica predominantly evergreen	79	88	70	73	78
Costa Rica overall forest	74	76	59	64	68
Costa Rica overall non-forest	32	16	32	59	35
Santa Rosa forest	16	34	24	34	27
Santa Rosa non-forest	78	48	72	92	73
Chamela-Cuixmala Forest	41	66	61	—	56
Chamela-Cuixmala non-forest	42	37	38	—	39

Table 3
Total forest cover for Costa Rica for each data set

Land cover map	Total forest area (km^2)
MODIS	39 409
GLC2000	36 961
IGBP	32 648
PROARCA	27 792
CR2000	*23 227*
Mayaux et al. (1998)	13 450

CR2000 control data set is shown in italics.

sets for forest at 34% (non-forest accuracies of 92% and 48%, respectively, Table 2). The lowest accuracy is from GLC2000 at 16% for forest (78% non-forest).

For the Chamela-Cuixmala region the dominant class from the land cover maps is cropland (GLC2000), mixed forest (MODIS) or evergreen broadleaf forest (IGBP) (Table 4). From the MX2002 database, the dominant class is forest with an extent of 78% (1925.6 km^2). With all forest classes combined, for total extent, MODIS was very close at 79% (1950.3 km^2) followed by IGBP at 70% (1728 km^2) and GLC2000 at 46% (1135.6 km^2). The highest accuracy for forest cover was from MODIS at 66% (non-forest accuracy 37%) indicating that while the amount of forest is close to the MX2002 data set, the precision (actual location) of the forest is incorrect (Table 2). The lowest forest accuracy was from the GLC2002 data set for forest (41%) with a non-forest accuracy of 42%. For all the land cover maps forest classes were assigned based on descriptions as well as nomenclature. For example, the classes such as "woody savannah" because of the description were also included in the forest classes along with those that were labelled "forest". Improved land cover classifications for all forest types could be expected with standardization and broader descriptions of the land cover classes (Jung et al., 2006).

3.3. Environmental services payments: forecasting carbon sequestration

Arroyo-Mora et al. (2005b) found a rate of change of +4.91% per year in forest cover for the period of 1986–2000 in a larger dry forest area encompassing the Santa Rosa study area. Assuming the same constant rate of change in forest cover for the 2000–2010 period, Table 5 and Fig. 2 illustrate the forecasted total forest area for each land cover map taking the results from this study as the year 2000 baseline for each. The CR2000 data set shows a total increase in forest cover by 2010 of 170 km^2 followed most closely by MODIS at 89.8 km^2 and with the greatest difference, PROARCA at 49 km^2. With the exception of PROARCA, the land cover maps produced a relatively similar forecast in total forest area. With the assumption that the ratio of forest stage (i.e. early: 22%, intermediate: 47%, late: 31%) found in the area by Arroyo-Mora et al. (2005a) remains relatively constant over that time period, and the values of Mg C/ha/stage from Table 1 are used the carbon gains forecasted by each data set are shown in Table 5. The greatest carbon gain is from the CR2000 data set with a total of 1 074 691 Mg C followed by MODIS with a total of 567 107 Mg C and with the greatest difference, PROARCA at 310 207 Mg C. If successional stages are disregarded and an average value of 91.32 Mg C/ha is used (Kauffman et al., unpublished), 1 553 401 Mg C are the forecasted gain from CR2000 in comparison to 819 720 Mg C (MODIS) or 448 386 Mg C (PROARCA) (Table 5). As can be seen in Fig. 2, the rate of change of the forest cover is much lower for all land cover maps in comparison to CR2000 and each year the difference is compounded. An unprecedented rate of change would be needed by models incorporating any of the land cover maps to reach the same final forecasted value of total forest area as shown by CR2000. From the projected increase in forest cover (2000–2010), the estimated value of carbon sequestration from the CR2000 data set is $US 500 109 ($US 29.4 ha^{-1}) with a range of $US 248 354–746 762 ($US 14.6–43.9 ha^{-1}) (Fig. 3). The MODIS land cover map is the closest in its projection with a projected value of carbon sequestration in 2010 at $US 263 904 and a range of $US 131 055–394 061 (Fig. 3).

4. Discussion and conclusion

While this study is not meant to cast an overly negative impression of the value of coarse resolution remotely

Table 4
Forest and non-forest classes from the land cover maps for Santa Rosa and Chamela

Location	Land cover map	No. forest classes (extent)	Dominant class (extent)	2nd dominant class (extent)	Other classes
Santa Rosa	GLC2000	6 (26%)	Cropland (70.1%)	Tropical broadleaved evergreen forest—open canopy (19%)	Grassland, water
Santa Rosa	IGBP	5 (14.3%)	Cropland (51.2%)	Cropland—natural vegetation mosaic (14.7%)	Savannah, grassland
Santa Rosa	MODIS	5 (35%)	Cropland (64.8%)	Woody savannah (2.3%)	Shrubland, savannah, grassland, cropland/natural veg. Mosaic
Santa Rosa	PROARCA	7 (21.9%)	Agriculture (72%)	Tropical broadleaf deciduous woodland (7.2%)	Tropical perennial graminoid grassland, forest-woodland-agriculture complex, urban-veg. complex, agriculture and urban-industrial
Chamela	GLC2000	6 (46.4%)	Cropland (50.6%)	Tropical broadleaved evergreen forest—closed canopy (28.8%)	Grassland, water, consolidated rock with sparse vegetation
Chamela	IGBP	5 (70.1%)	Evergreen broadleaved forest (26.7%)	Cropland (25%)	Savannah, grassland
Chamela	MODIS	5 (79.1%)	Mixed forest (29%)	Evergreen broadleaf forest (28.3%)	Shrubland, savannah, grassland, cropland, cropland/natural veg.mosaic

PROARCA is only available for Santa Rosa.

Table 5
Initial and 10 yr forecasted total forest cover and carbon gain (assuming a +4.91% increase in forest cover per year) for the Santa Rosa dry forest study area (total area 500 km^2)

	CR2000	GLC2000	IGBP	MODIS	PROARCA
Initial forest cover (km^2)	276.6	128.3	137.6	146.0	79.8
10 yr forecasted forest cover (km^2)	446.7	207.2	222.2	235.7	128.9
Change in forest cover (km^2)	170.1	78.9	84.6	89.8	49.1
Total carbon gain Mg C (allometric with stages from Table 1)	1 074 691	498 492	534 626	567 107	310 207
Total carbon gain Mg C (average 91.32 Mg C/ha)	1 553 401	720 540	772 769	819 720	448 386

sensed data used to create forest cover maps as tools for the estimation of payments of environmental services and carbon sequestration baselines, it does intend to illustrate that caution must be used when selecting the appropriate derived products for regional planning exercises and environmental monitoring assessments. The intended use varies among data sets and is generally based on the scale of the product and the amount of effort placed on in situ validation. The participation of local agencies and the consideration for region-specific complications is also imperative to the quality of the final products. Imagery, preferably medium resolution (i.e. 30 m), should be acquired for each study site/region projected for environmental services payments. The subsequent classification of the imagery to establish a baseline would then be specific to the area and a validation should also be conducted with the unique characteristics of the ecosystem in mind. Used with caution, medium and high resolution remotely sensed data are powerful tools for the study of land use–ecosystem interactions, for providing information to decision makers, and the regional application of integrated models.

Previous studies have examined the inconsistencies between forest cover data sets at national levels (e.g. Jung et al., 2006; Kerr et al., 2001; Kleinn et al., 2002; Mayaux et al., 1998). Inconsistencies are important to recognize because numerous problems with the accuracy estimations are due to under-estimation, over-estimation and general misclassification of forest and other land cover types (Jung et al., 2006). However, we believe there is a need to move beyond examining accuracies and to begin examining their implications that in many cases can be greater than differences in a simple measure of how accurate the forest extent is in comparison with other classification efforts. For example, the risk of using unreliable forest cover estimates for establishing baselines include forcing trading to increase global net emissions whereby any mitigation projects would be both misdirected and inefficient (Kerr et al., 2002).

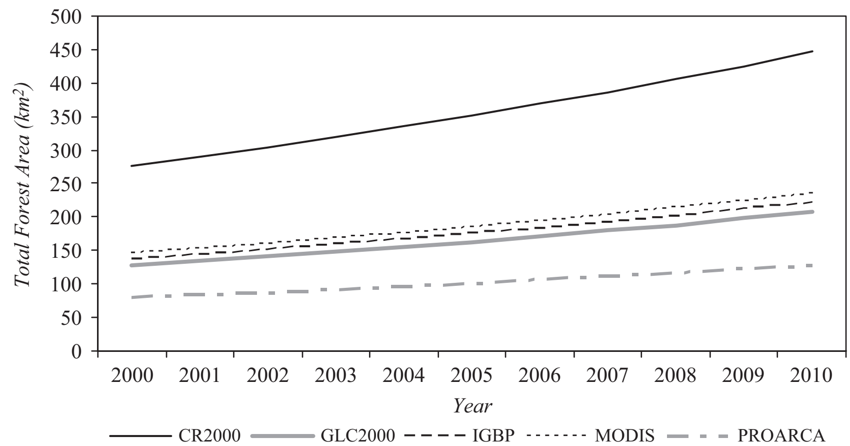

Fig. 2. Ten-year (2000–2010) forecasted total forest area (km^2) assuming a constant $+4.91\,km^2/yr$ rate of change.

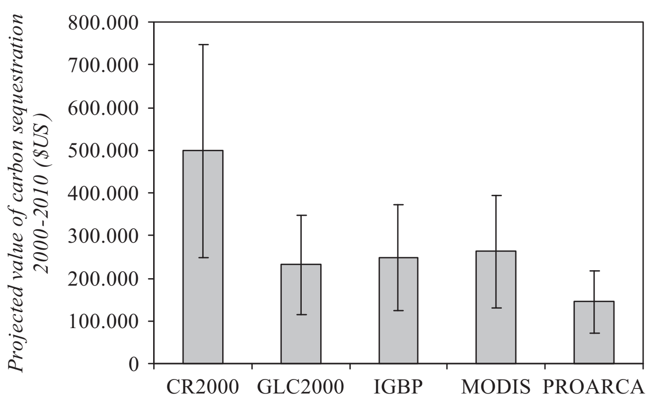

Fig. 3. Projected value (2000–2010) of carbon sequestration from the CR2000 map and the four land cover maps for the Santa Rosa study site. Mean \$/ha = 29.4US, Min \$/ha = 14.6US, Max \$/ha = 43.9US.

4.1. Implications of erroneous baseline estimates

Variations in baseline estimations may end up costing millions of misspent dollars over time and frustration in both the governmental and scientific spheres of political action. As indicated in Table 5, the relatively large underestimation of the baseline by the land cover maps for the Costa Rican example leads to compounded errors in forecasted carbon sequestration and it is unrealistic and erroneous to assume that if the rate of change is correct that the initial baselines are not important. For a project to be eligible for Emission Reduction Units (ERUs) under the United Nation's Framework Convention on Climate Change (UNFCCC) in the LULUCF category, it has to show a successful accumulation of sequestered carbon(UNFCCC, 2003b). One ERU is equal to 1 metric tonne of carbon dioxide equivalent (UNFCCC, 2003a). And the only way a project can claim ERUs or credits through the CDM, is if it can show sequestration of carbon above the baseline scenario. Any erroneous estimates of either the initial forest cover or change (i.e. deforestation rate) would lead to diverse and unrealistic values for the carbon stocks.

4.2. Consideration for the tropical dry forest

For the tropical dry forest specifically, the forest identified from wet season images is a mixture of both deciduous and semi-evergreen species as well as pasture lands with enough green herbaceous biomass to produce a spectral signature comparable to trees resulting in the non-forested areas to possibly be mistaken for forest (Fig. 4). Estimates of carbon would therefore be an overestimation of the baseline in these areas. In comparison, the forest area readily extracted from dry season images are most likely located in areas where the microclimate enables them to retain their foliage along with areas including species that practice inverse phenology. Kalácska et al. (2004, 2005) have shown that the areas in Santa Rosa that predominantly retain partial foliage in the dry season are found in the late successional stage. The spectral signature of dry woody matter does not resemble that of green vegetation (Asner, 1998; Kalacska et al., 2007) (Fig. 4) and therefore, these areas are likely to be missed by automated algorithms. In Chamela-Cuixmala, the Riparian forest (CH-L) which also retains its foliage in the dry season has a different species composition (i.e. more semi-evergreen species), different microclimate and different biomass (Quesada, unpublished observation) from other forest stages in the area. Yet, the other late/mature stage in Chamela-Cuixmala (CH-U) is almost entirely deciduous in the dry season reinforcing the complication that when the majority of the trees are without foliage, the spectral signature is comprised of a mixture from soil, leaf litter, rock, bark, etc., rather than predominantly green leaves (Asner, 1998) (Fig. 4).

In general, a higher accuracy for the non-forest classes compared to the forest classes can be seen for every classification and land cover map. For Santa Rosa the reason for the large discrepancy in accuracy for the two classes with the land cover maps is that the majority of the area is classified as non-forest. Therefore, the chance that a "forest" control point will fall into a pixel classified as

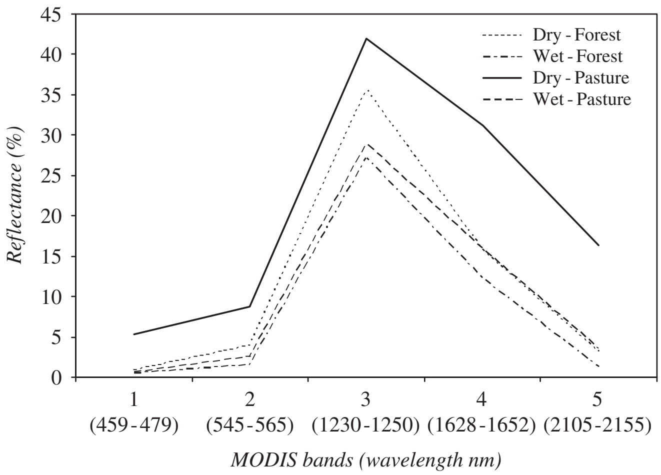

Fig. 4. Spectra of pasture and forest in the dry and wet seasons. Hyperion hyperspectral spectra were averaged to the spectral bands of the MODIS sensor.

forest is much less than the chance a "non-forest" control point will fall into a pixel classified as non-forest. For Chamela-Cuixmala, the location of the forest is incorrect (i.e. low accuracy) while the extent (i.e. total area) is generally close to what can be found on the ground. Thus, the application of inappropriate classification techniques will also result in large discrepancies. Methods must be flexible and may not all be used on an operational mapping project without extensive ground truth information. In addition, calibration or validation of large-scale maps without consideration of the ecological characteristics specific to each environment may contribute to the errors. These precautions must be taken in order to assure the most reliable baseline scenarios for both environmental services payments and carbon sequestration.

A common assumption is that at the spatial resolution of most global land cover maps ($1\,km^2$) the majority of the pixels is not homogenous in the land cover class they represent and therefore, under and/or over estimation of various classes is accepted. For the dry deciduous forest in Costa Rica Arroyo-Mora et al. (2005b) found that the mean patch size of forest was $1.07\,km^2$. In addition the forest patches are in general comparable in size or in some cases larger than the agriculture patches (i.e. dominant class in the land cover maps) (Table 4). These results indicate that although there may be many "mixed $1\,km^2$ pixels" there are still a sufficient number of "primarily forest pixels" in order for the deciduous forest to be present and included on land cover maps.

4.2.1. Deforestation pressure and implications for conservation

Based on examinations of socioeconomic uncertainty it has been stated that conservation research should focus in the wet forest life zones (Kerr et al., 2004). In Costa Rica with the collapse of the beef industry (thus changing the country's economy to cash crops such as pineapple and heart of palm that are grown in wet forest zones) and the short utility of tropical wet forest soils for agriculture, there are significant deforestation pressures in the wet forest life zones (Sánchez-Azofeifa et al., 2001; Subak, 2000). However, we argue that similar if not greater pressures also exist in the dry forest, compounded by the fact that they are practically non-existent in global land cover classifications and thus are not in the forefront of conservation policies(Sánchez-Azofeifa et al., 2005a, b). Due to low biotic and abiotic stresses and a comfortable climate, the dry forest has always been the preferred ecosystem for human settlement and animal husbandry (Ewel, 1999). The dry forest is globally extensive (42% of tropical forests are dry) but because of its appeal to human settlement it is also among the least protected (Murphy and Lugo, 1986). In Mesoamerica less than 1% has official conservation status, and only 2% is in patches large enough to attract the attention of conservation organizations (Janzen, 1988). Pfaff and Sánchez-Azofeifa (2004) illustrate large areas in the dry deciduous forest in Costa Rica where the pressure of deforestation is as high is in areas of wet forest. This along with the need to acknowledge their existence/location and the phenological complication accounting for the problems associated with estimating their true extent should make them a priority in global environmental services payments and carbon mitigation projects.

4.2.2. Cost of deforestation

In addition, the following example from Chamela-Cuixmala illustrates other potential problems that can arise from using various estimates of forest cover. The land tenure system around Chamela-Cuixmala favours subsistence and commercial crops, tourism and cattle grazing. Presently, the land is most valued for tourism rather than any other land use, including forest (Maass et al., 2005). However, the short-term return of such land uses does not make up for the long-term cost associated with these practices. For example, the clearing of the forests could result in either a scenario where certain pollinators will have to be brought to the area for various crops (which are of considerable value) or a scenario that could result in the loss of hundreds of thousands of dollars worth of crops (Maass et al., 2005). Both cases would result in very expensive endeavours compared to leaving the forest intact and utilizing the various services it could provide. If the maps being used by decision makers do not show the true extent of the forest, possible mechanisms for its protection cannot be considered.

However, in order to determine deforestation pressure (Pfaff and Sánchez-Azofeifa, 2004) or localize deforestation hot spots (Van Laake and Sánchez-Azofeifa, 2004), spatially reliable estimates of deforestation are needed; the basic requirement for which are accurate baseline forest cover maps from which to begin modelling.

4.3. Utility of remote sensing

A final broad question that must be considered concerns both the utility and facility of using remotely sensed data for payment of environmental services projects in general.

Rosenqvist et al. (2003) review the possible functions of remote sensing technology as part of decision support systems for the Kyoto Protocol. Two specific points from their review require special consideration for the use of remotely sensed data. First, the definition of ''forest'' from the Marrakesh Accords (UNFCCC, 2001a, 2003a) as referred to earlier and the subsequent standardization of ground control point verification (Subak, 2000). Second, based on the Bonn Agreements all forest and afforestation/reforestation/deforestation activities are defined based on land use rather than land cover (UNFCCC, 2001b). The implications of these are such that an area of cleared land that is expected to return to forest will still be counted as forest under the Kyoto protocol and will not count as deforestation (Rosenqvist et al., 2003). In addition, only direct-human-induced afforestation/reforestation/deforestation events will be considered (UNFCCC, 2003a, b). And, for reforestation specifically the land must have been cleared for a minimum of 10 years prior to human-induced reforestation (UNFCCC, 2003a). Thus, once a reliable land cover map of forest and non-forest areas is produced it must further be subject to additional in situ verification for land use classification.

4.4. Implications and questions to be addressed

We have shown that depending on which study is used, the estimations of environmental services payments, carbon content and the accuracy of the forest cover will vary accordingly. Until questions regarding nomenclature and types of forest classes are resolved, even for the simplest questions of ''how much forest is there?'' and ''where is the forest?'', discrepancies between various studies and problems with the estimations of payments of environmental services will persist. These discrepancies may end up costing hundreds of millions of dollars in erroneous payments and unsuccessful carbon mitigation projects as well as the irrevocable loss of biodiversity. In order to rectify the discrepancies, more rigorous methods including a greater emphasis on the collection of ground control data are required. In addition, a standardized description of the ''forest'' class which takes into account the heterogeneity and deciduousness of the dry forests as well as every class included in a land cover analysis would reduce the uncertainty associated with the current land cover classifications. Because, as shown, some large-scale global land cover maps are inherently unrealistic when examined closely at the ecosystem or country scales.

The implications of our study present a need for looking beyond simple accuracy assessments of these products and examining them in broader contexts such as environmental services payments. Fassnacht et al. (2006) identify the importance of understanding the limitations and caveats associated with using products created from remotely sensed data. The four key issues they identify are differences in direct and indirect models, the difference between class-based and continuous mapping models, scale and accuracy assessment. Similar issues illustrated in this study strengthen the need for a stronger awareness about how maps created from imagery should be used and the technical limitations associated with such data. Nevertheless, there is no doubt that remote sensing is a powerful tool for policy makers when used appropriately.

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