Emissions from land-cover change in Panama: uncertainty, dynamics, and perceptions

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À ma mère pour son amour qui m'a fait grandir,

À mon amoureux Francis pour m'avoir supporté dans la réalisation de mes rêves,

À mon fils Oscar qui m'inspire tous les jours à vouloir contribuer pour un monde meilleur

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List of Abbreviations

AD	Avoided Deforestation
AGB	Above-Ground Biomass
ANAM	Autoridad National del Ambiente
ANOVA	Analysis of Variance
BA	Basal Area
BAU	Business-As-Usual
BD	Basal Diameter
BEF	Biomass Expansion Factor
BPPS	Bosque Protector de Palo Seco
C	Carbon
CBMAP	Corredor Biológico Mesoamericano del Atlántico Panameño
CDM	Clean Development Mechanism
CEF	Centre of Forest Research
CO2	Carbon dioxyde
COP	Conference of Parties
CV	Coefficient of Variation
db MEM	Distance-based Moran's Eigenvector maps
DBH	Diameter at Breast Height
EU	European Union
FAO	Food and Agriculture Organization
FCD	Forest Carbon Density
FCPF	Forest Carbon Partnership Facility of the World Bank
FIDECO	Fideicomiso Ecológico de Panamá
FQRNT	Fonds Québécois pour la Recherche sur la Nature et les Technologies
FRA	Forest Resource Assessment
GCP	Ground Control Point
GEC3	Global Environmental and Climate Change Centre
GHG	Greenhouse Gas
GOFC-GOLD	Global Observation for Forest and Land Cover Dynamics
GPG	Good Practice Guidance
GPS	Global Positioning System
GV	Green Vegetation
IDRC	International Development Research Centre
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KP	Kyoto Protocol
LDA	Linear Discriminant Analysis
LUCC	Land-Use and Cover Change
MRV	Measuring, Reporting and Verifying

MSAVI	Modified Soil Adjusted Vegetation Index
MSAVIaf	Modified Soil Adjusted Vegetation Index aerosol free
NA	Not Available
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NPV	Non Photosynthetic Vegetation
NSERC	Natural Sciences and Engineering Research Council of Canada
PCA	Principal Component Analysis
PCoA	Principal Coordinates Analysis
PES	Payment for Environmental Services
RDA	Redundancy Analysis
REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries (including conservation, sustainable management of forest and forest carbon enhancement)
REL	Reference Emission Levels
RL	Reference Level
RS	Remote Sensing
SBSTA	Subsidiary Body on Scientific and Technical Advice
SD	Standard Deviation
SES	Social-Ecological System
SINAP	Sistema Natconal de Áreas protegidas
SOC	Soil Organic Carbon
STRI	Smithsonian Tropical Research Institute
SWIR	Short Wave Infrared
TER	Total Emission Reductions
UNFCCC	United Nations Framework Convention on Climate Change
UN-REDD	United Nations REDD Initiative
VIF	Variance Inflation Factor
VNIR	Visible Near Infrared
WB	World Bank
WD	Wood Density

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Preface

This is a manuscript-based thesis, consisting of a collection of papers of which I am the primary author. Chapter 1 and 2 have already been published; Chapter 3 has been submitted for publication and is accepted pending major modifications; and Chapter 4 is being prepared for submission. All chapters have been formatted in the style of the scientific journal Global Environmental Change. The manuscripts and associated journals are as follows:

Chapter 1

Pelletier, J., Kirby, K.R., Potvin, C. (2010) Significance of Carbon Stock Uncertainties on Emissions Reductions from Deforestation and forest Degradation in Developing Countries. Forest Policy and Economics 12 497-504.

Chapter 2

Pelletier, J., Ramankutty, N., Potvin, C. (2011) Diagnosing the Uncertainty and Detectability of Emission Reductions for REDD+ under Current Capabilities: an Example for Panama. Environmental Research Letters 6, 024005.

Chapter 3

Pelletier, J., Codjia, C., Potvin, C. Traditional Shifting Agriculture: Tracking Forest Carbon Stock and Biodiversity through Time in Western Panama. Global Change Biology. Accepted with major modifications.

Chapter 4

Pelletier, J., Gélinas, N., Potvin, C. (In preparation) Living Inside a Protected Area: Lessons for REDD+ with a Case Study from Panama.

Contributions of Authors

I am the primary author of all the studies included in this thesis. I formulated the hypothesis, designed the experiments, collected all the data (sometimes in collaboration with others; see below), analyzed the data and wrote the manuscripts. Catherine Potvin supervised the conceptual framework, experimental design, interpretation of the results, and writing of all manuscripts in this thesis.

For Chapter 1, Kathryn R. Kirby provided biomass information from her previously published work in Forest Ecology and Management (2008) and available in Table 3 of this chapter. She also contributed to the design of this research and provided extensive comments that greatly improved the manuscript.

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Thesis Abstract

Land use/cover change (LUCC) associated with tropical deforestation produces 6-17% of the total anthropogenic CO_2 emissions and is the second largest source of greenhouse gases globally. In Cancun 2010, a policy framework was adopted for the creation of a forest-related climate change mitigation mechanism to Reduce Emissions from Deforestation and forest Degradation in developing countries (REDD+). This mechanism would allow developing countries to be compensated by developed countries for reducing emissions from deforestation or for increasing removals by forests. In the context of REDD+, several methodological issues need to be solved, including better quantification of emissions from LUCC in order estimate credible emission reductions thus ensuring the integrity of the climate regime and the cost-efficiency of a REDD+ mechanism. Using Panama as a case study, the present research improved the understanding of uncertainties associated with the quantification of emissions from land-cover change based on a modeling approach. Forest carbon density is identified as one of the main sources of error. I showed that uncertainties associated with carbon density can affect substantially possible payment a country could receive to reduce its emissions. When performing a full diagnosis of uncertainty, four additional sources were identified including deforestation area, quality of land-cover maps, time interval between two land-cover assessments (snapshot effect) and carbon density of re-growing vegetation. In order to improve information on land-use dynamics and address the uncertainty related to the 'snapshot effect', I developed a new approach using a time series of medium resolution satellite images combined with a field survey of forest carbon stocks to track the impact of intervention over time. This approach provided a good proxy of forest carbon stock change and is a very promising avenue for monitoring dynamic land cover such as shifting cultivation. The methodological aspects of the thesis are complemented by an analysis of forest governance based on the perception of local residents living inside a protected area with ongoing deforestation. Local needs related to food security are identified as possible barrier to REDD+ implementation. The need to establish clear legal rights over access and use of forest resources to balance human needs and forest conservation under collaborative management approach is one of the great challenges that REDD+ will face.

Résumé

Le changement d'usage/couvert du sol associé à la déforestation tropicale produit 6-17% du total des émissions anthropogéniques de CO_2 et est la deuxième plus grande source de gaz à effet de serre à l'échelle globale. En 2010 à Cancun, un cadre politique visant la création d'un mécanisme d'atténuation des changements climatiques liés aux forêts a été adopté afin de Réduire les Émissions provenant du Déboisement et de la Dégradation des forêts dans les pays en développement (REDD+). Ce mécanisme permettrait au pays en développement d'être compensé par les pays développés pour la réduction des émissions provenant de la déforestation ou par l'augmentation de l'absorption par les forêts. Dans le contexte de la REDD+, plusieurs enjeux méthodologiques ont encore besoin d'être réglés, incluant une meilleur quantification des émissions provenant des changements d'usage et de couvert du sol afin d'estimer les réductions d'émission de façon crédible s'assurant ainsi de préserver l'intégrité du régime climatique et un bon rapport coût-efficacité. En utilisant le Panama comme étude de cas, la présente recherche a permis d'améliorer la compréhension des incertitudes associées à la quantification des émissions issues du changement de couvert par le biais de la modélisation. La densité de carbone forestier est identifiée comme étant la principale source d'erreur. De plus, il a été possible de montrer que les incertitudes associées à la densité du carbone forestier peuvent affectées substantiellement les possibles paiements qu'un pays peut recevoir pour réduire ses émissions. Après avoir effectué une analyse diagnostique complète de l'incertitude, quatre sources additionnelles ont pu être identifiées incluant les surfaces déboisées, la qualité des cartes de couvert, l'intervalle de temps entre deux analyses de couvert et la densité de carbone contenue dans la végétation qui repousse. Afin d'améliorer l'information disponible sur la dynamique d'usage du sol et d'aborder le problème de l'incertitude associé au *snapshot effect* (une photo instantanée d'un moment précis), j'ai développé une nouvelle approche en utilisant une série temporelle d'images satellite de moyenne résolution, combinée avec un inventaire des stocks de carbone forestier afin de suivre l'impact des interventions à travers le temps. Cette approche a permis d'obtenir un bon indicateur des changements dans les stocks de carbone forestier et est une avenue prometteuse pour faire le suivi de la dynamique d'usage du sol tel que dans le cas de l'agriculture migratoire. Les aspects méthodologiques abordés dans cette thèse sont

complémentés par une analyse de la gouvernance forestière basée sur la perception des résidents locaux vivant dans une aire protégée caractérisée par une déforestation continue. Les besoins locaux en lien avec la sécurité alimentaire sont identifiés comme pouvant être une barrière à la mise en œuvre de la REDD+. Le besoin d'établir des droits clairs quant à l'accès et à l'usage des ressources forestière afin d'établir un équilibre entre les besoins des gens et la conservation de la forêt, et ce par une approche d'aménagement collaboratif, est un des grands défis auquel REDD+ fera face.

General Introduction

Over the last few hundred years, substantial amounts of carbon dioxide (CO_2) have been released from forest clearing at high and middle latitudes and in the tropics since the latter part of the 20th century (IPCC, 2007). Land-use/cover change (LUCC) is currently the second largest anthropogenic source of CO_2 emissions worldwide after the burning of fossil fuel. Recent estimates evaluate its contribution at 6-17% of global emissions (van der Werf et al., 2009), equivalent to 1.3±0.7 Pg C yr^{-1} net emissions between 1990-2007 and 1.2 PgC yr^{-1} for 2008 (Pan et al., 2011). The relative contribution of LUCC emissions globally has decreased from 20% in 1990-2000 to 12% in 2008, due to an increase in fossil fuel emissions and below-average deforestation emissions in 2008 (Le Quéré et al., 2009).

According to the last Global Forest Resource Assessment (FAO, 2010), forests currently cover 31% of the Earth's total land area and store 289 Pg of C in their biomass alone. Five main carbon pools are typically identified, including aboveground living biomass, belowground living biomass, litter, woody debris, and soil organic carbon (IPCC, 2003). On average, tropical forests hold around 50% more carbon per hectare than forests outside the tropics (Houghton, 2005b). As a consequence, under equivalent rates of deforestation, more CO_2 emissions are released from tropical forests than from temperate or boreal forests.

Besides playing a critical role in the global carbon cycle, forests are important for the range of products and services they provide to society and for conservation of biodiversity (Costanza, 2006; Costanza et al., 1997; Gibson et al., 2011). They are also an integral part of the habitat and socio-cultural framework of a high number of people (Byron and Arnold, 1999), with almost all tropical forests having inhabitants in and around them (Ellis and Ramankutty, 2008). In the past LUCC was generally considered a local environmental issue. However, it is now recognized as being of global importance because widespread deforestation can potentially undermine the capacity of ecosystems to sustain services of global value (Foley et al., 2007; Foley et al., 2005; Lambin and Geist, 2006). The impacts of deforestation include the modification of the water regime, an increase of infectious disease, soil compacting, erosion, desertification, reduction of biological diversity, and climate change (DeFries and Rosenzweig, 2010; DeFries et al., 2004; MEA, 2005).

Deforestation occurs when forest is permanently converted to non-forest (UNFCCC, 2001) when another land-use is adopted. Forest is usually defined by a minimum land area, a minimum tree height and a minimum canopy cover threshold, the most commonly used definition being "land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%" (FAO, 2010). More precisely, deforestation can be permanent through the conversion of forests to croplands and pastures, or temporary through the partial removal of forests for shifting cultivation and selective logging (Houghton, 2003). Here it is important to mention that according to the United Nations Framework Convention on Climate Change (UNFCCC), only permanent removal is recognized as deforestation. Deforestation is deemed responsible for some 90% of the emissions caused by LUCC (IPCC, 2001). Forest degradation — a reduction of biomass within forests in the absence of land-cover change — is considered a significant contributor to global emissions equivalent to 5% of the emissions from deforestation for the world's humid tropics (Achard et al., 2004), 25-42% for tropical Asia (Houghton, 2005a; Houghton and Hackler, 1999) and 132% for tropical Africa (Gaston et al., 1998). Forest degradation is in fact now suspected of being responsible for an ever increasing part of GHG emissions (Asner et al., 2005; Foley et al., 2007; Lambin, 1999; Laporte et al., 2007; Numata et al., 2010; Souza Jr et al., 2005).

Main drivers of deforestation

Seminal work has been done to reach a global understanding of the causes and processes of LUCC in the tropics, mostly through meta-analyses of case studies available from the different continents (Angelsen and Kaimowitz, 1999; Geist and Lambin, 2001; Geist and Lambin, 2002; Rudel, 2005). These studies identify the complex interplay between proximate causes and underlying driving forces of tropical deforestation. Proximate causes refer to human activities at the local level that originate from intended land use and directly impact forest cover (e.g. agricultural expansion, wood extraction, and infrastructure extension), while underlying driving forces are social processes that affect the proximate causes such as demographic, economic, cultural, policy & institutions, and technological factors. According to Angelsen *et al.* (2009) the main agents of deforestation are subsistence farmers practicing shifting cultivation, cash crop smallholders, and large companies that clear land for crops and cattle. Together, they would be responsible for three-quarters of all tropical deforestation (IPCC, 2007). The role of population growth and shifting cultivation in deforestation and the linkage between poverty and deforestation is however being challenged (Chomitz et al., 2007; Geist and Lambin, 2001) with a greater role being attributed to the advancement of corporations at forest frontiers (Nepstad et al., 2006; Rudel et al., 2009). Agricultural expansion is by far, the leading land-use change associated with deforestation which was recently demonstrated spatially for the 80's and 90's (Gibbs et al., 2010). Understanding the causes of LUCC is fundamental if emissions from deforestation and forest degradation are to be reduced.

Advancements in the role of forests to mitigate climate change

In 2005, a new era of negotiations was launched to broaden the scope of the international climate regime. These negotiations included the creation of a mechanism to account for the role of forests in climate change under the United Nations Framework Convention on Climate Change (UNFCCC), leading to unprecedented advancements in international forest governance (Humphreys, 2006, 2008). A policy framework for the Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanism was agreed upon at the 16th UNFCCC Conference of the Parties (COP-16) in Cancun. The basic idea is that developing countries would be either compensated by developed countries for successfully reducing emissions, maintaining carbon stock and/or decreasing removals from forests, or that these emissions reductions could form part of an international carbon trading regime. REDD+ is a type of payment for ecosystem services because financial incentives will be conditional upon achievement of environmental outcomes (Clements, 2010).

The Cancun agreement aims at "slowing, halting, and reversing the loss and degradation of forests in developing countries" through five main activities: reducing deforestation, reducing forest degradation, sustainable management of forests, conservation, and the enhancement of forest carbon stocks (UNFCCC, 2010). Furthermore, the agreement establishes a phased approach towards REDD+ including a readiness phase, a capacity building and demonstration phase, and a performance-based payments for actions phase that would be fully measured, reported and verified (MRV) at a national level. The Cancun Agreement also requires developing countries to develop: 1) forest reference levels (RLs) taking into account historic data and national circumstances; 2) robust, consistent, transparent, and as accurate as possible national forest monitoring systems; and 3) information systems on social and environmental safeguards (UNFCCC, 2009).

The reactions towards the elaboration of a REDD+ mechanism have been highly optimistic, with studies indicating that REDD+ payment could be a cost-effective way to mitigate climate change (Stern, 2006) and that these unprecedented levels of funding towards forest conservation would promote biodiversity conservation as well as poverty alleviation of forest-dependent people, by the means of carbon markets (Ebeling and Yasue, 2008; Gullison et al., 2007; Hall, 2008; Kindermann et al., 2008; Laurance, 2007). Different studies have evaluated the opportunity costs of reducing emissions from deforestation, many point out that compensating different stakeholders is economically feasible in many circumstances at the current or even lower carbon prices on the market (Bellassen and Gitz, 2008; Coomes et al., 2008; Fisher et al.; Osafo, 2005; Pirard, 2008; Silva-Chavez, 2005). Other studies identify difficulties in obtaining possible co-benefits (Siikamaeki and Newbold, 2012) and risks for local communities and indigenous people posed by, among others, a possible recentralizing forest management and stimulating of corruption and elite capture (Clements, 2010; Hansen et al., 2009; Phelps et al., 2010; Potvin et al., 2007).

Ensuring the methodological and technical success of REDD+

Establishing a performance-based payment requires solving current methodological issues to quantify emissions and removals in a way that is accurate enough to have a credible system from both economic and environmental viewpoints (Grassi et al., 2008). Although LUCC is a smaller source of CO_2 than fossil fuel, its uncertainty, ±0.7 PgC yr^{-1}, is larger than the one associated with fossil fuel emissions, equivalent to ±0.5 PgC yr^{-1}

(Le Quéré et al., 2009). Challenges to improve the accuracy of estimates of emissions and removals from LUCC have been identified and include the uncertainty in forest area, forest area change and trends (Achard et al., 2004; DeFries et al., 2002; Fearnside, 2000; Grainger, 2008, 2011), in forest carbon density (Gibbs et al., 2007; Houghton et al., 2001), in the fate carbon after deforestation, and in the activities and processes included in the accountability of LUCC fluxes (Houghton, 2010; Ramankutty et al., 2007). Research is needed to secure the ability to provide measurable, reportable, and verifiable emissions and removals from forests (GOFC-GOLD, 2010), and establish accurate RLs to benchmark the amount of emission reductions from REDD+ at a national level (Angelsen et al., 2011).

Dealing with uncertainty

Uncertainty of a variable is the lack of knowledge of its true value. It depends on the state of knowledge, which in turn is dependable on available data and understanding of underlying processes. While quantifying uncertainty is relevant to scientific research and technological development, it is also important in the policy context since "decisions … [should] be made with as complete an understanding as possible of the current state of knowledge, its limitations and its implications" (Morgan, 1978).

The IPCC (2006) identifies eight reasons to explain why estimates in emissions and removals might differ from the true underlying values based on the work of Morgan and Henrion (1990) and Cullen and Frey (1999). These main causes of uncertainty applied to greenhouse gas (GHG) inventory are the lack of completeness, functional forms or models, lack of data, lack of representativeness of the data, statistical random sampling error, measurement error, misreporting or misclassification, and missing data (Frey *et al.*, 2006).

Conceptually, uncertainty stems from both random errors, which are inversely proportional to precision, and systematic errors (or bias), which refers to a lack of accuracy. The term precision describes the agreement among repeated measures and accuracy and represents the agreement between the true value and the average of repeated measured estimates. The two concepts are fully independent. Random error due to variability in observations about their mean can be reduced by taking sufficient observations, which is not the case with systematic error. Additional observations do not reduce systematic error, and so generally it comes to dominate the overall error. Systematic errors or the lack of accuracy may arise because of imperfections in conceptualization, models, measurement techniques or other ways to make inferences from the data, and its estimation is often much harder to quantify, involving a subjective processes as we are unaware of the true value (Morgan and Henrion, 1990).

According to IPCC's guidelines, uncertainty analysis is an essential component of GHG emissions and the inventory of removals. In order to identify which assumptions and uncertainties may significantly affect conclusions, both sensitivity and uncertainty analyses should be performed; the former to compute the effect of changes in input values or assumptions on the outputs and the latter to compute the total uncertainty induced in the output by quantified uncertainty in inputs and models (Morgan and Henrion, 1990). Being explicit about uncertainty entails estimating uncertainty around quantities, e.g. forest carbon stocks, about the appropriate functional form or models, e.g. allometric equations, and about disagreements among experts on both quantities and/or models (Morgan and Henrion, 1990).

The IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories assess the role of uncertainty analysis as a way "to help prioritize efforts to improve the accuracy of inventories in the future and guide decisions on methodological choice" (IPCC, 2000, 2006). In the context of the Cancun Agreement, National Greenhouse Gas Inventories serve to evaluate how developed countries are meeting their proposed quantified emissions reduction targets and uncertainties would impede a clear assessment of progress. In the case of REDD+, which includes a performance-based mechanism whereby developing countries would be compensated according to their success in reducing emissions or increasing removals from forests, uncertainty might affect the credibility of emission reductions. In the general guidance and reporting for uncertainty chapter, IPCC states that GHG inventories "should be accurate in the sense that they are neither over- nor underestimated as far as it can be judged, and precise in the sense that uncertainties are reduced as far as practicable" (Frey *et al.*, 2006). Grassi et al (2007) notes that in the REDD+ context "not overestimating the reduction of emissions" would be a way to be conservative thus securing real emission reductions.

Reducing uncertainty bears a cost. As such, attempts to reduce uncertainty will be guided by scientific principles and constrained by economical limitations. It is therefore important to optimize financial allocation to reducing uncertainty vs implementing actions to tackle the climate problem (Fenichel and Hansen, 2010). In this sense, it is important to focus efforts to reduce uncertainty with a priority to those inputs that have the most impact on overall uncertainty (IPCC,2006), including for the cost-efficiency of REDD+ monitoring and reporting readiness (Pelletier et al, 2011). The challenge facing policy makers and negotiators is to manage uncertainty by designing a workable and affordable institutional framework (Gupta, 2003) that would make REDD+ work for the integrity of the climate and the wallet.

Elaborating a strategy for REDD+

Developing countries interested in participating in REDD+ need to build national strategies based on a comprehension of the drivers of deforestation and an understanding of their own national circumstances. Previous experiences that successfully addressed deforestation in the tropics are rare and often only local in scale; the complexity of driving forces of LUCC calls for major reforms, at times well outside the forest sector (Clements, 2010; Sunderlin and Atmadja, 2009). For example, land tenure, inter-sectorial coherence, benefit-sharing, transparency, and accountability in monitoring, are all governance issues that would need to be addressed if real changes on the ground are to be attained (Davis et al., 2009; Larson, 2011). The fact that tropical deforestation results predominantly from clearing for agricultural expansion denotes the necessity for an evaluation of policy options for development that would help reconcile forest conservation and production goals (Angelsen, 2010). One policy option is the creation of protected areas which usually experience lower rates of deforestation than unprotected areas (Scharlemann et al., 2010), although there is some controversy surrounding this approach because of the link that has been found between poverty and protected areas which may have high costs on local land-users (Angelsen, 2010; Ferraro, 2002; West et al., 2006).

It is important to obtain lessons from existing attempts to reduce deforestation to prevent the implementation of actions that could serve the interests of the international community and even of developing nations but be done at the expense of the poor, marginalized, and mostly indigenous forest-dependent peoples (Peskett et al., 2006). To be widely adopted and sustained, REDD+ mechanisms must deliver sufficient financial benefits to the people who live on the land (Potvin et al., 2007) and be based on the recognition of human rights and the participation of local land users in decision-making.

Reducing LUCC emissions in Panama

The previous sections have emphasized the role of forests in sustaining important ecosystem services and functions, focusing mainly on the global carbon cycle, the challenges and complexity of LUCC as well as the uncertainties plaguing estimates of CO_2 emissions from this sector. We then reviewed the existing framework proposed to understand and address the causes of deforestation. We followed this by briefly discussing the challenges in the elaboration of the REDD+ mechanism, to address the international desire to halt deforestation without jeopardizing the livelihoods of forest-dependent peoples. These elements provide the overall context of the research presented here.

Chapters 1, **2**, and **3** focus on methodological issues that would allow for improvements in the accuracy and monitoring of emissions and removals from LUCC using Panama as a case study. Panama is a small Central American country that has shown interest in participating in REDD+, and was one of the first countries to receive financial support from the World Bank Forest Carbon Partnership Initiative (FCPF) and the United Nations-REDD initiative (UN-REDD) for REDD readiness. LUCC is the main source of the greenhouse gas (GHG) emissions in Panama, mostly caused by agricultural expansion (ANAM, 2000). In **Chapter 1**, using a modeling framework for Holdridge's Moist Tropical life zone, I evaluate the uncertainty associated with forest carbon density estimates and its significance on emission estimates and the possible financial compensation that Panama could receive for avoiding deforestation.

Chapter 2 scales up the analysis to the national level. Using a sensitivity analysis on a land-cover emissions model, I propose a diagnosis of the main sources of error plaguing the quantification of CO_2 emissions from land-cover change in Panama. Then, using Monte Carlo uncertainty propagation on key parameters identified by the sensitivity analysis, I quantified the overall uncertainty around estimates of emissions per life zone as well as for the entire country. Different scenarios of deforestation avoidance were compared to evaluate the ability of detecting the significance of emission reductions given the current levels of uncertainty.

One of the main sources of error identified in Chapter 2 is related to a lack of knowledge of land-use dynamics when a long time interval exists between two land-cover assessments. In **Chapter 3**, I track the land-use dynamics associated with shifting cultivation practices using a time series of medium-resolution satellite images and a field survey of forest carbon stocks. This approach is based on the hypothesis that tracking interventions over time could allow us to monitor forest carbon stock change in the area. The proposed methodology was validated with a field survey in Palo Seco Forest Reserve, in Western Panama, using participatory methodologies to monitor land cover and forest carbon stocks.

Engaging with the locals in Chapter 3, opened the door for a study of residents' perceptions of forest conservation in Palo Seco Forest Reserve (**Chapter 4**). The protected area system in Panama is extensive and one of the main strategies used by the Panamanian government to protect forest cover. However, challenges in harmonizing social interests and forest conservation interests are commonly encountered. This study provides input from the people living in the Palo Seco forest reserve, and from other stakeholders, on possible strategies for maintaining forests for REDD+ while improving livelihoods.

REFERENCES

Achard, F., Eva, H.D., Mayaux, P., Stibig, H.J., Belward, A. (2004) Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles 18, 12.

ANAM, (2000) Primer Inventario Nacional sobre los Gases a Efecto Invernadero., Primera comunicación Nacional sobre Cambios Climáticos. Autoridad Nacional del Ambiente, Panama, Repúplica de Panamá, p. 18pp.

Angelsen, A. (2010) Policies for reduced deforestation and their impact on agricultural production. Proceedings of the National Academy of Sciences of the United States of America 107, 19639-19644.

Angelsen, A., Boucher, D., Brown, S., Merckx, V., Streck, C., Zarin, D., (2011) Modalities for REDD+ Reference Levels: Technical and Procedural Issues, prepared for the Government of Norway by the Meridian Institute, p. 18.

Angelsen, A., Kaimowitz, D., (1999) Rethinking the Causes of Deforestation: Lessons from Economic Models., The World Bank Research Observer. The International Bank for Reconstruction and Development / THE WORLD BANK, Washington, DC., pp. 73–98.

Angelsens, A., with, Brockhaus, M., Kanninen, M., Sills, E.O., Sunderlin, W.D., Wertz-Kanounnikoff, S., (2009) Realising REDD+: National strategy and policy options, in: CIFOR (Ed.), Bogor, Indonesia.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N. (2005) Selective logging in the Brazilian Amazon. Science 310, 480-482.

Bellassen, V., Gitz, V. (2008) Reducing Emissions from Deforestation and Degradation in Cameroon - Assessing costs and benefits. Ecological Economics 68, 336-344.

Byron, N., Arnold, M. (1999) What futures for the people of the tropical forests? World Development 27, 789-805.

Chomitz, K.M., Buys, P., De Luca, G., Thomas, T., Wertz-Kanounnikoff (2007) At Loggerheads?: Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests. The International Bank for Reconstruction and Development/ The World Bank, Washington, D.C.

Clements, T. (2010) Reduced Expectations: the political and institutional challenges of REDD. Oryx 44, 309-310.

Coomes, O.T., Grimard, F., Potvin, C., Sima, P. (2008) The Fate of Tropical Forest: Carbon or Cattle? Ecological Economics 65, 207-212.

Costanza, R. (2006) Nature: ecosystems without commodifying them. Nature 443, 749-749.

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., vandenBelt, M. (1997) The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Cullen, A.C., Frey, H.C. (1999) Probabilistic techniques in exposure assessment : a handbook for dealing with variability and uncertainty in models and inputs. Plenum Press, New York.

Davis, C., Daviet, F., Nakhooda, S., Thuault, A., (2009) A review of 25 readiness plan idea notes from the World Bank Forest Carbon Partnership Facility, WRI Working Paper. World Resources Institute, Washington, DC.

DeFries, R., Rosenzweig, C. (2010) Toward a whole-landscape approach for sustainable land use in the tropics. Proceedings of the National Academy of Sciences of the United States of America 107, 19627-19632.

DeFries, R.S., Foley, J.A., Asner, G.P. (2004) Land-use choices: balancing human needs and ecosystem function. Frontiers in Ecology and the Environment 2, 249-257.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townshend, J. (2002) Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proceedings of the National Academy of Sciences of the United States of America 99, 14256-14261.

Ebeling, J., Yasue, M. (2008) Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 1917-1924.

Ellis, E.C., Ramankutty, N. (2008) Putting people in the map: anthropogenic biomes of the world. Frontiers in Ecology and the Environment 6, 439-447.

FAO, (2010) Global Forest Resources Assessment 2010: Main report, FAO Forestry Paper 163. Food and Agriculture Organization, Rome, p. 340 pp.

Fearnside, P.M. (2000) Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46, 115-158.

Fenichel, E.P., Hansen, J.A. (2010) The opportunity cost of information: an economic framework for understanding the balance between assessment and control in sea lamprey (Petromyzon marinus) management. Canadian Journal of Fisheries and Aquatic Sciences 67, 209-216.

Ferraro, P.J. (2002) The local costs of establishing protected areas in low-income nations: Ranomafana National Park, Madagascar. Ecological Economics 43, 261-275.

Fisher, B., Lewis, S.L., Burgess, N.D., Malimbwi, R.E., Munishi, P.K., Swetnam, R.D., Turner, R.K., Willcock, S., Balmford, A. Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. Nature Climate Change 1, 161-164.

Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P. (2007) Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Frontiers in Ecology and the Environment 5, 25-32.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. (2005) Global consequences of land use. Science 309, 570-574.

Gaston, G., Brown, S., Lorenzini, M., Singh, K.D. (1998) State and change in carbon pools in the forests of tropical Africa. Global Change Biology 4, 97-114.

Geist, H.J., Lambin, E., (2001) What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence, LUCC Report Series 4. International Human Dimensions Programme on Global Environmental Change (IHDP) International Geosphere-Biosphere Programme (IGBP), Louvain-la-Neuve, Belgium, p. 136.

Geist, H.J., Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52, 143-150.

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A. (2007) Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., Foley, J.A. (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences of the United States of America 107, 16732–16737.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378-381.

GOFC-GOLD, (2010) A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation, GOFC-GOLD Report version COP16-1. GOFC-GOLD Project Office, Natural Resources Canada, Alberta, Canada.

Grainger, A. (2008) Difficulties in tracking the long-term global trend in tropical forest area. Proceedings of the National Academy of Sciences of the United States of America 105, 818-823.

Grainger, A. (2011) Uncertainty in the construction of global knowledge of tropical forests. Progress in Physical Geography 34, 811-844.

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D. (2008) Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates. Environmental Research Letters 3, 035005 (035012pp.).

Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., Nobre, C. (2007) Tropical Forest and Climate Policy. Science 316, 985-986.

Gupta, J., Olsthoorn, X., Rotenberg, E. (2003) The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention. Environmental Science & Policy 6, 475-486.

Hall, A. (2008) Better RED than dead: paying the people for environmental services in Amazonia. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 1925-1932.

Hansen, C.P., Lund, J.F., Treue, T. (2009) Neither fast, nor easy: he prospect of Reduced Emissions from Deforestation and Degradation (REDD) in Ghana. International Forestry Review 11, 439-455.

Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus Series B-Chemical and Physical Meteorology 55, 378-390.

Houghton, R.A. (2005a) Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945-958.

Houghton, R.A., (2005b) Tropical deforestation as a source of greenhouse gas emissions., in: Moutinho, P., Schwartzman, S. (Eds.), Tropical Deforestation and Climate Change, Belem, Brazil and Washington, D.C., USA, pp. 13-21.

Houghton, R.A. (2010) How well do we know the flux of CO2 from land-use change? Tellus Series B Chemical and Physical Meteorology 62, 337-351.

Houghton, R.A., Hackler, J.L. (1999) Emissions of carbon from forestry and land-use change in tropical Asia. Global Change Biology 5, 481-492.

Houghton, R.A., Lawrence, K.T., Hackler, J.L., Brown, S. (2001) The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Global Change Biology 7, 731-746.

Humphreys, D. (2006) Logjam: Deforestation and the Crisis of Global Governance. Earthscan, London.

Humphreys, D. (2008) The politics of 'Avoided Deforestation': historical context and contemporary issues. International Forestry Review 10, 433-442.

IPCC, (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC/OECD/IEA/IGES, Hayana, Japan.

IPCC, (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies (IGES), Japan.

Frey, H.C., Penman J., M., Hanle, L., Monni, S., Ogle, S., (2006) General Guidance and Reporting: Uncertainties, in: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), IPCC Guidelines for Natinational Greenhouse Gas Inventories.

IPCC, (2007) IPCC Fourth Assessment Report: Climate Change 2007. IPCC, Geneva, Switzerland.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., Beach, R. (2008) Global cost estimates of reducing carbon emissions through avoided deforestation. PNAS 105, 10302-10307.

Lambin, E.F. (1999) Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. Global Ecology and Biogeography 8, 191-198.

Lambin, E.F., Geist, H.J. (2006) Land-Use and Land-Cover Change: Local Processes and Global Impacts. Springer, Berlin.

Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S., Goetz, S.J. (2007) Expansion of industrial logging in Central Africa. Science 316, 1451-1451.

Larson, A.M. (2011) Forest tenure reform in the age of climate change: Lessons for REDD+. Global Environmental Change 21 540-549.

Laurance, W.F. (2007) A new initiative to use carbon trading for tropical forest conservation. Biotropica 39, 20-24.

Le Quéré, C., Raupach, M.R., Canadell, J.G., Marland, G., et al. (2009) Trends in the sources and sinks of carbon dioxide. Nature Geosci 2, 831-836.

MEA, (2005) Millenium Ecosystem Assessment, www.milleniumassessment.org.

Morgan, M.G. (1978) Bad Science and Good Policy Analysis. Science 201, 971.

Morgan, M.G., Henrion, M. (1990) Uncertainty, A guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. Cambridge University Press, New York.

Nepstad, D.C., Stickler, C.M., Almeida, O.T. (2006) Globalization of the Amazon soy and beef industries: Opportunities for conservation. Conservation Biology 20, 1595-1603.

Numata, I., Cochrane, M.A., Roberts, D.A., Soares, J.V., Souza, C.M., Jr., Sales, M.H. (2010) Biomass collapse and carbon emissions from forest fragmentation in the Brazilian Amazon. Journal of Geophysical Research 115, G03027.

Osafo, Y.B., (2005) Reducing emissions from tropical forest deforestation: applying compensated reduction in Ghana., in: Moutinho, P., Schwartzman, S. (Eds.), Tropical Deforestation and Climate Change. Amazon Institute for Environmental Research (IPAM) and Environmental Defense, Belem, Brazil and Washington, D.C., USA, pp. 63-72.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D. (2011) A Large and Persistent Carbon Sink in the Worlds Forests. Science 333, 988-993.

Pelletier, J., Ramankutty, N., Potvin, C. (2011) Diagnosing the uncertainty and detectability of emission reductions for REDD+ under current capabilities: an example for Panama Environmental Research Letters 6, 024005.

Phelps, J., Webb, E.L., Agrawal, A. (2010) Does REDD plus Threaten to Recentralize Forest Governance? Science 328, 312-313.

Pirard, R. (2008) Estimating opportunity costs of Avoided Deforestation (REDD): application of a flexible stepwise approach to the Indonesian pulp sector. International Forestry Review 10, 512-522.

Potvin, C., Coomes, O.T., Grimard, F. (2007) Will RED Work Where It Should? Science.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., Houghton, R.A. (2007) Challenges to estimating carbon emissions from deforestation. Global Change Biology 13, 51-66.

Rudel, T.K. (2005) Tropical Forests: Regional Paths of Destruction and Regeneration in the Late Twentieth Century. Columbia University Press, New York.

Rudel, T.R., DeFries, R., Asner, G., Laurance, W.F. (2009) Changing Drivers of Deforestation and New Opportunities for Conservation. Conservation Biology 23, 1396-1405.

Scharlemann, J.P.W., Kapos, V., Campbell, A., Lysenko, I., Burgess, N.D., Hansen, M.C., Gibbs, H.K., Dickson, B., Miles, L. (2010) Securing tropical forest carbon: the contribution of protected areas to REDD. Oryx 44, 352-357.

Siikamaeki, J., Newbold, S.C. (2012) Potential Biodiversity Benefits from International Programs to Reduce Carbon Emissions from Deforestation. Ambio 41, 78-89.

Silva-Chavez, G.A., (2005) Reducing greenhouse gas emissions from tropical deforestation by applying compensated reduction to Bolivia., in: Moutinho, P., Schwartzman, S. (Eds.), Tropical Deforestation and Climate Change. Amazon Institute for Environmental Research (IPAM) and Environmental Defense., Belem, Brasil and Washington, D.C., USA., pp. 73-86.

Souza Jr, C.M., Roberts, D.A., Monteiro, A. (2005) Multitemporal Analysis of Degraded Forests in the Southern Brazilian Amazon. Earth Interactions 9, 1-25.

Stern, N. (2006) The Stern Review: the Economics of Climate Change. Cambridge University Press, Cambridge, UK.

UNFCCC (2001) Definitions, Modalities, Rules and Guidelines Relating to LULUCF Activities under the Kyoto Protocol (Annex to the Marrakesh Accords).

UNFCCC, (2009) Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries, Decision 4/CP.15.

UNFCCC, (2010) Outcome of the work of the Ad Hoc Working Group on long-term Cooperative Action under the Convention, Draft decision [-/CP.16]. United Framework Convention on Climate Change.

van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.S.J., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J., Randerson, J.T. (2009) CO2 emissions from forest loss. Nature Geoscience 2, 737-738.

West, P., Igoe, J., Brockington, D. (2006) Parks and peoples: The social impact of protected areas. Annual Review of Anthropology 35, 251-277.

Contributions to knowledge

Chapter 1 provides a comparison of estimates of forest carbon stocks in the context of an international mitigation mechanism known as the Reduction of Emissions from Deforestation and forest Degradation (REDD+). This is the first study to highlight the importance of uncertainty in forest carbon density on the economics of REDD for developing countries. I show that the high uncertainties unveiled could affect the economic viability of REDD+. While previous work has quantified the propagation of uncertainty in forest inventories caused at the individual tree level by measurements, sampling, and allometric models, this research integrates the level of uncertainty found at a regional level and calls for improvements on this major source of error in quantifying emissions from land-cover change.

Chapter 2 is the first study to provide a full diagnosis of the key sources of error associated with the emissions from land-cover change at a national scale, using the real data available in a developing country, in this case Panama, and testing for deforestation reduction scenarios derived from governmental input. By propagating the uncertainties with a Monte Carlo analysis, we provide a clear illustration of the implications of uncertainty for REDD+. This is also the first research to demonstrate that under current levels of uncertainty, Panama would have to reduce deforestation substantially (by 50%) in order to produce emission reductions outside the uncertainty margins. This study focuses on providing recommendations to countries involved in REDD+ activities to improve the accuracy of their forest-related emissions and removals and propose cost-effective ways to reduce error in emission reductions and thus help orient readiness activities in developing countries.

Building on information obtained from Chapter 2 which identified the scant knowledge on the land-use dynamics after deforestation, **Chapter 3** advances knowledge on ways to monitor shifting cultivation to estimate changes in forest carbon stocks. It is the first study to use a time series of remote sensing images to detect forest intervention as a way to predict forest carbon stock changes in the tropics. Reported emissions from land-cover change typically ignores the land-use dynamics associated with shifting cultivation with the risk of overestimating emissions if areas are classified as new deforestation or of underestimate emissions if fallow vegetation, part of a clearing cycle, is detected as forest regrowth. By combining field surveys with remote sensing analysis, this research brings novel insights on the impacts of shifting cultivation on carbon stock change and biodiversity over time. This methodological approach offers a new option for monitoring shifting cultivation areas in developing countries.

Working in the same area as chapter 3, **Chapter 4** is the first study to the best of our knowledge to propose the much needed input of local perceptions from people living in a protected area on forest conservation as a way to inform an effective and successful REDD+ strategy. Palo Seco Forest Reserve (BPPS), located in Western Panama, is a multiple-use protected area characterize by a large indigenous resident population that could be described as economically poor, and that depends on the access and use of natural resources for their livelihood. BPPS is the protected area experiencing the highest rates of forest cover change of all protected areas in the country and was identified by the Panamanian government as a priority area for this study. To support a strategy that will promote forest conservation, it is crucial to take into account local residents' perceptions to identify constraints and possible synergies in order to balance human needs and forest conservation. Food security, an overarching determinant of forest cover change for local residents is the main constraint identified by this research but a facet that has been largely unexplored in REDD+ literature. The research pinpoints the need of clarifying legal rights in order to build trust and enable collaboration with local residents.

Linking Statement 1

In the Introduction section, uncertainty in forest carbon density was mentioned as one pending technical issue to measure emissions from LUCC more accurately. In Chapter 1, five different estimates of forest carbon stock for Holdridge's Moist Tropical life zone in Panama were used to model emissions from land-cover change. Comparing the resulting range of emissions allowed us to study the significance of the uncertainty associated with forest carbon density on the economic incentives necessary to avoid deforestation. This chapter integrates forest carbon estimates from previous field inventories done by our research group in the Moist Tropical life zone in Panama. It provides a review that explains why it is still hard to have accurate estimates of biomass at a regional level in the tropics. The contribution of error associated with the use of different allometric models of tree biomass is discussed. A clear illustration of the economic implication of using different forest carbon density estimates, including the available global default value, on the payment received for reducing deforestation by 10% in the Moist Tropical forest is provided.

CHAPTER 1:

Significance of Carbon Stock Uncertainties on Emissions Reductions from Deforestation and forest Degradation in Developing Countries

Status: Pelletier J, Kirby Kr, Potvin C (2010) Significance of Carbon Stock Uncertainties on Emissions Reductions from Deforestation and forest Degradation in Developing Countries. Forest Policy and Economics, 12 497-504.

ABSTRACT

An historical agreement was reached in Bali under the United Nations Framework Convention on Climate Change, encouraging countries to initiate actions to reduce emissions from deforestation and forest degradation in developing countries (REDD). In this context, we use a Panama-based example to show the impacts of the current levels of uncertainty in forest carbon density estimates on GHG baseline estimation and estimations of emission reductions. Using five aboveground tree carbon stocks estimates for Moist Tropical forest in a simulation study, we found a difference in terms of annual CO_2 emissions of more than 100% between the lowest and the highest estimates. We analyze the economic significance to show that when comparing the income generated for the different forest carbon density estimates to the cost of 10% reduced deforestation, the break-even point differs from US$6.74 to US$16.58 per ton of CO_{2e} between highest and the lowest estimate. We argue that for a country such as Panama, improving the quality of forest carbon stock estimates would make economic sense since the highest forest carbon density estimates were developed nationally while the lowest estimate is the global default value. REDD could result in a huge incentive for forest protection and improved forest management, in consequence, we highlight that progress on the incorporation of uncertainty analysis and on the mitigation of the main sources of error in forest carbon density estimates merit further methodological guidance.

INTRODUCTION

In December 2007, the highly publicized “Bali Action Plan” was adopted at the conference of the United Nations Framework Convention on Climate Change (UNFCCC). This decision initiated a new era of discussion on the possible role of forests in the post-Kyoto climate regime to the Convention (Ott *et al.* 2008). The decision *encourages* parties to initiate activities to Reduce Emissions from Deforestation and forest Degradation (REDD) in developing countries (Article 3 in UNFCCC, 2007). Negotiations for the inclusion of tropical forests as a new avenue to climate change mitigation started in December 2005 as the governments of Papua New Guinea and Costa Rica brought the possibility of taking action to reduce emissions from deforestation in developing countries to the attention of the UNFCCC (UNFCCC, 2005). Although deforestation accounts for 10-25% of all greenhouse gases (GHG) emissions (Houghton, 2005a), previous attempts to reach an international agreement on forests under the UNFCCC have failed (LePrestre, 2005). During the negotiations of the Kyoto Protocol (KP), a variety of concerns restricted acceptable land use mitigation activities to reforestation and afforestation (Streck & Scholz, 2006). The decision reached in Bali is therefore historical.

The program of work on REDD agreed to in Bali “*invited Parties to submit their views on how to address outstanding methodological issues*” (Article 7 in UNFCCC, 2007). The establishment of baseline that allows the demonstration of reductions in emissions from deforestation is one of the pending issues (DeFries et al. 2007). The notion of a baseline takes its roots in the rules guiding the Clean Development Mechanism (Decision 17/CP. 7, Marrakesh Accords). Carbon trading between developed and developing countries indeed requires project proponents to provide a baseline against which the real carbon removals are estimated (Auckland et al. 2003). It was suggested that a baseline for reducing emissions from deforestation could be based on historical emissions or could use historical emissions as input for business as usual projections (Olander et al, 2008) and would serve at calculating emission reductions. One proposal is that evaluation of baselines could rest on: 1) the assessment of changes in land-use/land-cover (Activity Data) and 2) the associated carbon stock change (Emission factor) (GOFC-GOLD, 2009).

During the REDD negotiations, several developed countries -- EU, USA, Canada, Japan -- as well as the Rainforest Coalition, an informal group of countries led by Papua New Guinea and Costa Rica, claimed that emission reductions from deforestation must be estimated against a national baseline of GHG emissions (Potvin & Bovarnik, 2008). National baselines are presented by their proponents as the only way to control leakage, or displacement of deforestation activities within a country. Conversely, a loose group of Spanish-speaking Latin American countries led by Columbia argues that national baselines are currently inapplicable because many countries lack the capacity and the necessary information to determine a national baseline for GHGs or do not fully control their territory. In Bali, when discussing the EU 's proposed Indicative Guidance, countries agreed that demonstration activities could be done at both the national and the sub-national level. However, the issue remained contentious up to Copenhagen's 15th Conference of the Parties (Potvin, C., *personal observation*). Regardless of the scale at which baseline emissions are estimated, accuracy and precision are needed to ensure that the reductions compensated for in a hypothetical REDD mechanism are properly quantified (Mollicone et al., 2007a).

In Poznan at the fourteenth Conference of the Parties, the importance given to reference emission levels justified the request for an expert meeting on the topic (Article 6 in UNFCCC, 2008). The report on this meeting identifies outstanding issues and highlights the presence of gaps in data and data quality including *inter alia* standing stocks per hectare, estimates of biomass density, development of biomass expansion factors, and allometric equations and improved estimates at the levels of forest type and forest ecosystem (UNFCCC, 2009a). Furthermore, a technical paper of the UNFCCC on the cost of implementing methodologies and monitoring systems for REDD signals that the majority of non-Annex I countries have limited capacity in providing complete and accurate estimates of GHG emissions and removals from forests (UNFCCC, 2009b).

The SBSTA decision taken in Copenhagen (COP 15) signals that REDD-plus national monitoring systems need to provide estimates that are "transparent, consistent, as far as possible accurate, and that reduce uncertainties, taking into account national capabilities and capacities." (UNFCCC, 2009c)

The purpose of this paper is to assess the impact of uncertainties in forest carbon density on baseline estimation. We present this assessment in the context of the UNFCCC discussions on the current capability of developing countries to estimate emissions baselines and other methodological issues to REDD. Using Panama as an example, we illustrate the sensitivity of a land-cover change emission model in regards to estimates of forest carbon density and discuss the different sources of error of these estimates. We examine the effect of uncertainties on possible payments for emission reductions from deforestation. We also highlight research needs for the improvement of forest carbon density estimation.

METHODS

Panama's Moist Tropical Forest is its most extensive forest ecosystem, covering ~ 3,000,000 ha (Figure 1). It is also the forest ecosystem suffering the greatest encroachment from deforestation nationally. To estimate the baseline for the Moist Tropical Forest of Panama we elaborated a modeling approach based on Ramankutty *et al.* (2007). The model estimated the carbon flux from land-cover change over the entire forest ecosystem. It contains two sections: 1) a land-cover transition model based on a first-order Markov matrix to simulate the land-cover dynamic following deforestation, and 2) a book-keeping carbon cycle model to estimate the flux resulting from the land cover dynamics. All model computer simulations were performed using MATLAB, version 7.6. The equations to the model can be found in appendix of Ramankutty *et al.* (2007).

1) Land-cover transition model

To parameterize the land-cover transition model, we compared two land-cover maps (1992 and 2000) to assess annual deforestation and obtain a transition probability matrix for the Moist Tropical Forest. These land-cover maps as well as a life zone map following Holdridge's classification were provided by Panama’s Autoridad Nacional del Ambiente (ANAM). They were initially converted from vector to raster with a pixel size of 100 m by 100 m (area of 1 hectare) under Lambert-Azimuthal Equal Area projection, using ArcGIS 9.3 ESRI®. Then, in order to obtain the Markov matrix of annual land cover transition probabilities, we took the eight root of the matrix. This matrix included five land cover classes: Mature forest, Secondary forest, Fallow, Agriculture, and Other (ANAM/ITTO, 2003). Under this ANAM/ITTO classification, the mature forest category includes all forests and plantations with more than 80% tree cover. The secondary forest category covers re-growing, previously cleared, and degraded forest having between 60% and 80% tree cover. The fallow category includes re-growing vegetation following agricultural land abandonment with less than five years of age. The agriculture category was sub-divided into the average percentage area cover with annual crop, permanent crop, and pasture found in Panama's agricultural census (Contraloría, 2001). The "Other" category joined urban areas, inland water (such as lakes or reservoirs), and lowland vegetation liable to flooding (such as salt marshes). For the sake of this modeling exercise, the deforestation was assumed to be zero prior to 1992. The only anterior land-cover map that would be available for the country (Magallon, F., *personal communication*), was based on the conversion of Garver (1947) verbal descriptions into a land-cover map for 1947 (Heckadon-Moreno, 1984; Wright and Samaniego, 2008). We decided not to include this assessment in the present study, but we acknowledge the fact that ignoring past deforestation could underestimate emissions for this time period (Ramankutty *et al.*, 2007). See Table 1 for the transition probabilities among land-cover classes. The land-cover transition model was validated by running the simulation for the base year 1992, and by comparing the model's results with the reality observed on the 2000 map. The results concur to 100% for the year 2000.

2) Bookkeeping Carbon Cycle model

This section of the model served to calculate annual CO_2 fluxes originating from the land-cover change. We modeled the changes in aboveground live biomass only, since it was suggested that in the context of REDD, for monitoring purposes, only the dominant carbon tree pool would be considered as a key category (GOFC-GOLD, 2009). The model tracks the annual emissions and uptake following reclearing and regrowth of fallow and secondary forest as well as carbon fluxes from permanent cultivation growth and clearing. Only changes in land cover are considered here; neither changes in land use management nor the effect of natural or human disturbances (e.g. fire, insect outbreak) were considered although they could possibly affect carbon fluxes.

Emissions released following clearing events were partitioned into three pools. Following Gutierrez (1999), 60% of the carbon emissions were considered as immediately lost into the atmosphere due to burning of plant material, 34% were released at slower rate from decay of residues left on site, and 6% were temporarily stored in wood products. We used rates of decay estimates from the Brazilian Amazon for both dead material left on site and harvested woody material (Ramankutty et al., 2007) due to similar forest conditions, especially temperature and precipitation (FAO, 2006), and because we are unaware of any national decay data. Non-CO_2 gases (e.g. methane, nitrous oxide) liberated during the burning process and that depend on burning efficiency were not accounted for.

Re-clearing of secondary forest already present in 1992 was assigned a mean value of 80.4 tC/ha emitted (or transferred) from the forest C pool at the time of harvest and carbon re-accumulation was set at a rate of 3.4 tC ha^{-1} yr^{-1} (FRA, 2005). The re-growth and re-clearing of secondary forest formed since 1992 followed a logistic function in proportion to the mature forest mean carbon density relative to the age of the forest, where exponential growth in trees is considered in the first years (Potvin and Gotelli, 2008) and where we assumed the carbon stocks to be recovered completely after 75 yrs (Alves et al., 1997; Brown & Lugo, 1990). Secondary forest growth was simulated starting at the age of 5 years in order to correspond to the land cover classification, and in particular to distinguish it from the fallow category. Only net changes in annual fallow areas were accounted for at a value of 35.4 tC ha^{-1}. The reverting mature forest class was assigned a plantation growth rate. Pasture land was assumed to store 4.2 tC ha^{-1}, with a three-year burning cycle (Kirby and Potvin, 2007). Permanent crops were considered to sequester carbon at a rate of 10 tC $ha^{-1}yr^{-1}$, while the clearing of permanent crops was assigned a mean value of 50 tC ha^{-1} (IPCC, 2003; Schroeder, 1994). Table 2 summarizes the parameters used in this model.

Sensitivity to forest carbon density

The model served to test the sensitivity of different aboveground live tree carbon density (hereafter forest carbon density- FCD) estimates on baseline estimation and emission reductions from REDD. For the purpose of this analysis, we kept the above values constant in order to test the effect of different estimates of FCD only. Five published FCD estimates were used in the model described above to calculate annual CO_2 emissions from land-cover change in Panama's Moist Tropical Forest between 1992 and 2000 (IPCC, 2003, Chave, et al., 2004; FRA, 2005; Kirby and Potvin, 2007). With the exception of the IPCC default value (Annex 3A.1, Default tables for section 3.2 Forest land, Table 3A.1.2.), all estimates were evaluated using ground-based forest measurements. The four Panama-based estimates differ in terms of both the inventory methods used to collect tree dimension data and the allometric equations used to relate tree dimensions to oven-dried biomass (Table 3). To assess the impact of allometric models on FCD uncertainty, we include two FCD values derived from a single set of inventory data (Kirby and Potvin, 2007). In all cases, where biomass rather than carbon stocks were reported in the original studies, we assume carbon to account for half of the biomass value (Houghton, 2003).

Sensitivity of the economics of REDD

Uncertainties in forest C density have implications for the economics of REDD. To illustrate this point, we carried out a back-of-the-envelope financial analysis for the case study in Panama to compare the potential income generated from REDD with the cost of avoiding deforestation. To look at the effect of forest carbon estimates on potential estimated income from REDD, we applied a 10 % reduction of annual deforestation or the equivalent of 2,170 ha of mature forest to be conserved yearly, for a period of eight years. This would be a realistic figure according to a government official (Potvin *et al.*, 2008). We evaluated the total emissions reductions (TER) for the five FCD estimates by comparing the business-as-usual (BAU) model results to a scenario of 10% annual avoided deforestation (AD) scenario, which can be expressed by:

1) $TER_c = \Sigma f_c(BAU, t) - f_c(AD, t)$ where,

TER_c is the total emission reductions in tons of C ha^{-1} per FCD estimate

f_c is the model where the subscript C=1 to 5 for one of the five FCD estimates,

BAU stands for Business-As-Usual deforestation,

AD stands for a 10% deforestation reduction and,

t= 1 to 8 for the eight years of avoided deforestation.

Then, we calculated the potential income by multiplying the total emission reductions to a range of market values of US$0.50 to US$ 30 by ton of CO_2e. The potential income generated for emission reductions from avoiding deforestation was calculated as:

2) $I_c = TER_c * P$ where,

P is the price of carbon where P= 0.5 to 30 (\$US t^{-1} CO_2 *e*)

I_c is the income for FCD estimate 'c'

This hypothetical income generated through REDD, that depends upon the carbon density of forests, was compared with the cost of avoiding deforestation, a value that is independent of carbon density. Using a discount rate of 5%, Potvin *et al.* (2008) estimated the overall cost to avoid deforesting 5,000 ha per year in Panama for 25 years at US$114,663,825 with an annual mean of US$4,586,553, including the land opportunity cost, the cost of protection, transaction, and administration. This value corresponds to a net present value of \$917.31 ha^{-1} yr^{-1}. The land-use opportunity cost was estimated in comparison with the income generated by small-scale cattle ranching, a preferred land use in Panama (Coomes *et al.*, 2008). Other available estimates of land use opportunity costs falls within the same range of values (Louis Berger Group, 2006; Barzev, 2008).

The total cost of REDD was estimated as follows:

3) $TCD = 917.31 \text{ X } \Sigma(AD*t)$ where,

TCD signifies the total cost of avoided deforestation,

\$917.31 is the overall cost of avoiding deforestation on a *per ha* basis (ha^{-1} yr^{-1}) and,

t= 1 to 8 for the eight-year avoided deforestation period.

Note that the area of deforestation avoidance is cumulative through time, and that protected forest involves an annual cost. Finally, the break-even point of REDD is located where the income from REDD equals the overall cost of avoiding deforestation.

RESULTS

Based on the analysis described above, applying the five different estimates of FCD, the sensitivity to changes in this parameter for the Moist Tropical Forest between 1992 and 2000 proves notable. In a single year, the choice of C stock density can result in estimates of annual emissions between the models that differ by 8.0 million t CO_{2e}, with a 103% increase in value between the lowest and the highest estimates (Figure 2). When we compare the two FCD values obtained from a single set of inventory data but differing in terms of allometric equations used (Kirby and Potvin, 2007), the difference between the mean annual emissions for these two estimates is 48%. Our simulation also shows that the IPCC default value yields the lowest estimates of all including the more recent independent scientific values.

In addition, we assessed the impact of the FCD estimates on the evaluation of emission reductions. We calculated emission reductions by comparing the scenario of 10% deforestation reduction with a reference emission level (BAU baseline) for each FCD estimate. When we compared mean annual emission reductions over the eight-year period obtained using these five estimates, the difference between the lowest and the highest estimate is 144%.

Part of the difference between the emission estimates is attributable to the model structure that calculates the carbon density held in regrowing secondary forest as a function of time relative to the proportion of mature FCD (see logistic equation in Table 2). Logically, secondary forest should not have higher carbon density than mature forest unless specific forest carbon management is adopted.

For the economic analysis, we also used a scenario of a 10% reduction in annual deforestation for the calculation. This corresponds to a reduction of 2,170 ha per year. Using published overall cost estimate per hectare for Panama (Potvin et al 2008), our analysis shows the significance of the choice of carbon density estimate on the economics of REDD. Not surprisingly, the results show that the net economic benefit of REDD would be higher, due to greater emissions reductions accounted as a result of higher estimated carbon density. Figure 3 shows that the economic significance of the choice of carbon density estimate increases as the market value per ton of CO_2e increases. It may not matter so much which one is chosen when C price is $1-5, but it becomes much more meaningful at $15-20 per ton of CO_2e.

Yet when comparing the income generated for the different FCD estimates to the cost of 10% reduced deforestation, the break-even point differs from US$6.74 to US$16.58 per ton of CO_{2e} for the highest vs. the lowest FCD estimate (Table 4). Thus the economic feasibility of REDD will depend directly on the values of FCD. From a developing country perspective, knowledge of forest carbon stocks is a necessary condition to decide the price at which selling carbon credits become profitable or not.

DISCUSSION

Sources of Uncertainty

The contribution of uncertainties in FCD as a source of error in the quantification of emissions from land-cover change in the tropics is receiving a growing body of attention (GOFC-GOLD, 2009; Grassi et al., 2008; Mollicone et al., 2007b; Ramankutty et al., 2007; Houghton, 2005b). FCD is known to vary regionally depending on temperature, elevation, precipitation, tree species composition, disturbance, and soil fertility (Laurance et al., 1999; Clark & Clark, 2000; Malhi et al., 2006; Urquiza-Haas et al., 2007). Beyond this natural variation, FCD uncertainties can also result from estimation methods. Two main constituents can affect FCD estimates: inventory protocol and the method used to convert tree measurement to biomass. A third error factor, which we did not explore in our simulations, stems from uncertainty in accounting for other forest C pools.

Primarily, the error imputable to the inventory protocol includes random sampling error (plot size and number of data points) and, lack of representativeness or systematic error (e.g. possible biases in selecting attractive forests) (IPCC, 2000; Chave et al., 2004; Grassi et al., 2008). The latter is often harder to quantify, but nonetheless important.

Secondly, uncertainties can also stem from methods of biomass estimation whether relying on allometric equations or on biomass expansion factors (BEFs). The error imputable to the choice of allometric model to estimate FCD has also been discussed in the literature where authors have qualified it as being of crucial importance (Clark & Clark, 2000; Keller et al., 2001; Chave et al., 2004; Chave et al., 2005). In temperate regions, allometric models have been developed for individual tree species, whereas in the tropics the high tree diversity renders this approach impractical. For example, in a 50 ha forest plot in Barro Colorado Island, Panama, approximately 300 tree species have been identified (Condit et al., 2004; Hubbell, 2006). As a surrogate, scientists have developed generalized allometric models that use measured forest attributes and relate them statistically to measurements obtained from the destructive sampling of a large number of trees (Brown, 1997; Chave et al., 2005). Results from the literature show that the choice of allometric equations can explain an error of greater than 20% of aboveground tree biomass estimates (Clark & Clark, 2000; Keller, 2001; Chave et al., 2004) and can be amplified when large trees are numerous (Kirby and Potvin, 2007).

Besides this, another method to convert forest inventory data to FCD estimates is the use of biomass expansion factors (BEFs), which employ ratios to convert wood volume to biomass (e.g. Table 3, FRA (2005) estimate). BEFs require the estimation of wood volumes, followed by application of expansion factors to account for non-inventoried tree components, then propagating sources of error along the way (Brown, 1997; Nogueira *et al.,* 2008). The uncertainty in conversion from tree volume to carbon content is one of the major gaps in carbon accounting at regional and national level, but also the scant presence of quantitative uncertainty analysis (apart from expert knowledge) is obvious (Fehrmann and Kleinn, 2006; Lehtonen *et al.*, 2007). With both methods, the relative accuracy and precision depends on the underlying data used to derive the allometric model or the ratio volume to biomass. In this study, we illustrated the point by using two allometric equations on the same inventory data; the different results prove that allometric models are another important source of uncertainty in the quantification of emissions from land-cover change.

Ultimately, as noted in other studies, another source of uncertainty roots from the inclusion of distinct field measurements or adjustments for other C pools, explaining also the discrepancy in total FCD estimates (Houghton et al., 2000; Keller, 2001). It is important to emphasize that in this exercise we focused our attention on uncertainty in aboveground live FCD only. While countries willing to engage in REDD could participate by only tracking changes in aboveground live biomass, an obliged key category (GOFC-GOLD, 2009), including a range of estimates for the other C pools (roots, woody debris, litter, soil organic carbon (SOC)) would further increase the overall uncertainty of the reference emissions levels. For the case of the SOC, studies signal that land-cover change could result in changes in soil carbon density by 13 to 59 % (Guo and Gifford, 2002) and that conversion of forest to cropland generally leads to a loss of soil carbon (Murty *et al.*, 2002). The studies of SOC in Panama that we reviewed showed stability in this carbon pool across land-use types (with no difference between forest, pasture, young fallow, old fallow, subsistence agriculture plots and native tree plantations) (Kirby and Potvin, 2007; Potvin *et al.,*2004; Tschakert *et al.*, 2007; Schwendenmann & Pendall, 2006). However, Kirby and Potvin (2007) note that none of these studies tracked changes in SOC at the same site through time, which would provide more reliable estimates of changes in SOC with land-use change. In conclusion, while the inclusion of other pools in a REDD national (or sub-national) monitoring system will most probably depend on the financial resources available; efforts to improve and standardize methodologies for monitoring carbon in these pools are also needed.

IPCC default value

A set of guidelines produced by the Intergovernmental Panel on Climate Change (IPCC), opens three methodological avenues to countries for estimating national greenhouse gases (GHGs), according to different levels of quality from a very coarse to a highly detailed assessment. Emissions categories that are considered key because of their significant influence on a country's total inventory of direct GHGs should be estimated using sophisticated calculations and nationally developed models, and have been termed Tier 2 and 3 methodologies depending on the level of details provided. For less important emissions categories, or when data is not available, default values and simpler approaches (for example, Tier 1 methodologies (IPCC, 2003)) could be used.

The UNFCCC's technical paper on the cost of implementing methodologies and monitoring systems for REDD (UNFCCC, 2009b) suggests that many developing countries do not have the financial and/or human capital necessary to produce national estimates to comply with Tier 2 or 3 methodologies. As a result, IPCC default values are likely to be used to evaluate REDD. However, in countries such as Panama where the forests are tall and dense, using the IPCC default values would be disadvantageous for the country, although the estimate would be conservative as emission reductions would not be overestimated. The REDD negotiation hinges around the notion that developing countries would be paid to reduce emissions on the basis of tradable emissions reduction units expressed as t CO_{2e}. Using default values that underestimate carbon density would allow developing countries willing to engage in the fight against deforestation to be able to claim less than they could if they improved their inventories. Thus, improving the quality of FCD estimates in tropical forests can be justified economically compared to the use of a global default value. While accurate and precise estimates of FCD in tropical areas will likely translate into higher REDD estimates (Grassi et al, 2008), our simple economic calculation indicates that this might result in a lower break-even price when a nation sells hypothetical REDD credits. We argue here, that in turn this would enhance the likelihood of successful REDD implementation since countries with tall and dense tropical forest would have to successfully halt forest cover loss over a smaller surface area to reach a given emission reduction.

Tier 2 or 3 methodologies: overcoming technical challenges

In the absence of a well-designed, regional-scale sampling effort, the choice of the "right" estimate for the carbon density of Panama's Moist Tropical Forests is quite subjective. The inventories described in Chave et al. (2004) and Kirby and Potvin (2007) are most probably not representative of Panama's Moist Tropical Forests as a whole because they are based on relatively small-scale samples that did not cover the entire region. The estimate calculated for the Forest Resource Assessment (2005) comes from different scientific and commercial forest inventories from the 1970's forward that did not follow a single, standard methodological protocol. For instance, some inventories only measured trees ≥ 60 cm diameter-at-breast-height (dbh) while others started at ≥ 40 cm. Even if adjusted *a posteriori* to produce a single estimate of carbon density per hectare, the result has a low confidence level. Therefore, technical guidance from forest scientists is needed if developing countries such as Panama want to improve the quality of FCD estimates and tackle a Tier 2-3 methodology to REDD.

Moreover, the case of forest degradation, explicitly included in the Decision 2/CP13 (UNFCCC, 2007), is an example where the carbon density changes might be hard to estimate but those estimates will affect the income generated. Forest degradation is a land-cover modification rather than conversion which results from human activities that partially reduce FCD without regeneration in a reasonable time frame (in the order of a decade) (Lambin, 1999; Defries et al., 2007). In the context of current UNFCCC discussions, forest degradation is essentially a non-temporary reduction of FCD. According to the UNFCCC definition of forest set at a minimum area of 0.05-1.0 ha with 10-30% tree crown cover, a substantial decrease in the carbon density can occur without any change in classification (Sasaki and Putz, 2009). The potential for selective logging, *inter alia*, to lead to an important reduction of FCD has been highlighted in both empirical and theoretical studies (Gaston et al., 1998; Asner et al., 2005a; Asner et al., 2005b; Bunker et al., 2005; Souza et al., 2005; Laporte et al., 2007; Putz *et al.*, 2008). The variability of FCD in the landscape is expected to increase due to the impacts of varying intensities of selective logging or other agents such as fires on forest structure and composition (Gerwing, 2002). The comparison with uncertain estimates of mature forest might result in quite small conservative emission reductions.

One way in which scientists could contribute to the REDD agenda is by ensuring that countries have access to the most recent data and methods on carbon density estimates. In this context, the recently published research by Gibbs et al. (2007) presenting an updated global map of national-level carbon density estimates deserves mention. Also, the effort of the Center for Tropical Forest Science to undertake a full assessment of carbon density changes in their ten large (16 to 52 ha each) forest plots world-wide should be applauded (Chave et al., 2005; Chave et al., 2008). In a recent study for the Amazon basin, allometric equations from directly weighed trees in small-scale samples in specific forest types were used to assess uncertainties and improve models for biomass estimates based on wood-volume data from large-scale inventories (Nogueira *et al.,* 2008). Further efforts to improve our knowledge of tropical FCD should be encouraged.

In conclusion, REDD is surging forward as a historical incentive for forest protection and improved forest management in the tropics. Our results suggest that the impact of uncertainties in FCD is an outstanding methodological issue that could affect the quantification of emission reductions and potential payments to developing countries for avoiding deforestation. The model applied for this study concentrated on the effects of changes in land cover and did not consider changes in land use management or the effect of natural or human disturbances (e.g. fire, insect outbreak) possibly affecting carbon flux. Our study highlights that it may be worthwhile for national governments to recognize the potential value of improving/developing good national forest carbon monitoring systems in the context of REDD, under the UNFCCC. Finally, REDD methodological guidance should include the means to stimulate continuous progress on the incorporation of uncertainty analyses and on the mitigation of the main sources of error in the quantification of emissions from land-cover change, particularly on forest carbon density estimates.

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REFERENCES

Alves, D.S., Soares, J.V., Amaral, S., Mello, E.M.K., Almeida, S.A.S., DaSilva, O.F., Silveira, A.M., 1997. Biomass of primary and secondary vegetation in Rondonia, Western Brazilian Amazon. Global Change Biology 3, 451-461.

ANAM/ITTO, 2003. Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. In. Autoridad Nacional del Ambiente, Panama, Republica de Panama, p. 107 pp.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N., 2005a. Selective logging in the Brazilian Amazon. Science 310, 480-482.

Asner, G.P., Knapp, D.E., Cooper, A.N., Bustamante, M.M.C., Olander, L.P., 2005b. Ecosystem Structure throughout the Brazilian Amazon from Landsat Observations and Automated Spectral Unmixing. Earth Interactions 9, 1-31.

Auckland, L., Costa, P.M., Brown, S., 2003. A conceptual framework and its application for addressing leakage: the case of avoided deforestation. Climate Policy 3, 123-136.

Barzev, R., 2006. Programa multifase de desarrollo sostenible de Bocas del Toro autoridad nacional del ambiente. In, Segundo Informe de Avances. ANAM.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests. In, Forestry Paper Food and Agriculture Organization, Roma, p. 94 pp.

Brown, S., Lugo, A.E., 1990. Tropical Secondary Forests. Journal of Tropical Ecology 6, 1-32.

Bunker, D.E., DeClerck, F., Bradford, J.C., Colwell, R.K., Perfecto, I., Phillips, O.L., Sankaran, M., Naeem, S., 2005. Species loss and aboveground carbon storage in a tropical forest. Science 310, 1029-1031.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87-99.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R., 2004. Error propagation and scaling for tropical forest biomass estimates. Philosophical

Transactions of the Royal Society of London Series B-Biological Sciences 359, 409-420.

Chave, J., Condit, R., Muller-Landau, H.C., Thomas, S.C., Ashton, P.S., Bunyavejchewin, S., Co, L.L., Dattaraja, H.S., Davies, S.J., Esufali, S., Ewango, C.E.N., Feeley, K.J., Foster, R.B., Gunatilleke, N., Gunatilleke, S., Hall, P., Hart, T.B., Hernandez, C., Hubbell, S.P., Itoh, A., Kiratiprayoon, S., LaFrankie, J.V., de Lao, S.L., Makana, J.R., Noor, M.N.S., Kassim, A.R., Samper, C., Sukumar, R., Suresh, H.S., Tan, S., Thompson, J., Tongco, M.D.C., Valencia, R., Vallejo, M., Villa, G., Yamakura, T., Zimmerman, J.K., Losos, E.C., 2008. Assessing evidence for a pervasive alteration in tropical tree communities. PLoS Biology 6, 455-462.

Clark, D.B., Clark, D.A., 2000. Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137, 185-198.

Condit, R., Aguilar, S., Hernandez, A., Perez, R., Lao, S., Angehr, G., Hubbell, S.P., Foster, R.B., 2004. Tropical forest dynamics across a rainfall gradient and the impact of an El Nino dry season. Journal of Tropical Ecology 20, 51-72.

Contraloría, 2001. VI Censo Agropecuario. In. Contraloría General de la República - Dirección de Estadística y Censo República de Panamá.

Coomes, O.T., Grimard, F., Potvin, C., Sima, P., 2008. The Fate of Tropical Forest: Carbon or Cattle? Ecological Economics 65, 207-212.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., de Souza, C., 2007. Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science & Policy 10, 385-394.

Food and Agriculture Organization. 2006. Global forest resources assessment 2005: progress towards sustainable forest management. FAO Forestry Paper 147. Food and Agriculture Organization, Rome, Italy.
Available online at: http://www.fao.org/DOCREP/008/a0400e/a0400e00.htm.

Fehrmann, L., Kleinn, C., 2006. General considerations about the use of allometric equations for biomass estimation on the example of Norway spruce in central Europe. Forest Ecology and Management 236, 412-421.

Garver, R.D., 1947. National survey of the forest resources of the Republic of Panama. State Department, Washington, D.C., USA.

Gaston, G., Brown, S., Lorenzini, M., Singh, K.D., 1998. State and change in carbon pools in the forests of tropical Africa. Global Change Biology 4, 97-114.

Gerwing, J.J., 2002. Degradation of forests through logging and fire in the eastern Brazilian Amazon. Forest Ecology and Management 157, 131-141.

Gibbs, H.K., Brown, S., Niles, J.O., Foley, J.A., 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environmental Research Letters 2.

GOFC-GOLD, 2009, Reducing greenhouse gas emissions from deforestation and 46 degradation in developing countries: a sourcebook of methods and procedures 47 for monitoring, measuring and reporting, GOFC-GOLD Report version COP14-2, 48 (GOFC-GOLD Project Office, Natural Resources Canada, Alberta, Canada).

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D., 2008. Applying the conservativeness principleto REDD to deal with the uncertainties of the estimates. Environmental Research Letters 3, 035005 (035012pp.).

Louis Berger Group, 2006. Establecimiento de un mecanismo financiero para pago por servicios ambientales (PSA) en la cuenca hidografica del Canal de Panama. In. Louis Berger Group, Panamá.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345-360.

Gutierrez, R., 1999. Inventario Nacional de Gases de Efecto Invernadero para el modulo “Cambio de Uso de la Tierra y Silvicultura”. . In: ANAM (Ed.). República de Panamá, Panamá, p. 115 pp.

Gutierrez, R., 2005. Forest Resource Assessment 2005. In. Food and Agriculture Organization-Forest Department, Rome, p. 118p.

Heckadon Moreno, S., 1984. Panama’s expanding cattle front: the Santeno campesinos and the colonization of the forests. Dissertation. University of Essex, Colchester, UK.

Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus Series B-Chemical and Physical Meteorology 55, 378-390.

Houghton, R.A., 2005a. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945-958.

Houghton, R.A., 2005b. Tropical deforestation as a source of greenhouse gas emissions. In: Moutinho, P., Schwartzman, S. (Eds.), Tropical Deforestation and Climate Change, Belem, Brazil and Washington, D.C., USA, pp. 13-21.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H., 2000. Annual fluxes or carbon from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301-304.

Hubbell, S.P., 2006. Neutral theory and the evolution of ecological equivalence. Ecology 87, 1387-1398.

IPCC, 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (Edited by J Penman, D Kruger, I Galbally, T Hiraishi, B Nyenzi, S Emmanul, L Buendia, R Hoppaus, T Martinsen, J Meijer, K Miwa and K Tanabe) The Institute for Global Environmental Strategies for the IPCC and IPCC National Greenhouse Gas Inventories Programme. Hayama, Kanagawa, Japan. ISBN 4-88788-000-6

IPCC. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry (Edited by J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner). The Institute for Global Environmental Strategies for the IPCC and IPCC National Greenhouse Gas Inventories Programme. Hayama, Kanagawa, Japan. ISBN 4-88788-003-0.

Keller, M., Palace, M., Hurtt, G., 2001. Biomass estimation in the Tapajos National Forest, Brazil: examination of sampling and allometric uncertainties. Forest Ecology and Management 154, 371-382.

Kirby, K.R., Potvin, C., 2007. Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. Forest Ecology and Management 246, 208-221.

Lambin, E.F., 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. Global Ecology and Biogeography 8, 191-198.

Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S., Goetz, S.J., 2007. Expansion of industrial logging in Central Africa. Science 316, 1451-1451.

Laurance, W.F., Fearnside, P.M., Laurance, S.G., Delamonica, P., Lovejoy, T.E., Rankin-de Merona, J., Chambers, J.Q., Gascon, C., 1999. Relationship between soils and Amazon forest biomass: A landscape-scale study. Forest Ecology and Management 118, 127-138.

Lehtonen, A., Cienciala, E., Tatarinov, F., Makipaa, R., 2007. Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic. Annals of Forest Science 64, 133-140.

LePrestre, P., 2005. Protection de l'environnement et relations internationales. Armand Colin, Paris.

Malhi, Y., Wood, D., Baker, T.R., Wright, J., Phillips, O.L., Cochrane, T., Meir, P., Chave, J., Almeida, S., Arroyo, L., Higuchi, N., Killeen, T.J., Laurance, S.G., Laurance, W.F., Lewis, S.L., Monteagudo, A., Neill, D.A., Núñez Vargas, P., Pitman, N.C.A., Quesada, C.A., Salomao, R., Silva, J.N.M., Torres-Lezama, A., Terborgh, J., Vasquez Martinez, R., Vinceti, B., 2006. The regional variation of aboveground live biomass in old-growth Amazonian forests. . Global Change Biology 12, 1107-1138.

Miles, L., Kapos, V., 2008. Reducing greenhouse gas emissions from deforestation and forest degradation: Global land-use implications. Science 320, 1454-1455.

Mollicone, D., Achard, F., Federici, S., Eva, H.D., Grassi, G., Belward, A., Raes, F., Seufert, G., Stibig, H.J., Matteucci, G., Schulze, E.D., 2007a. An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. Climatic Change 83, 477-493.

Mollicone, D., Freibauer, A., Schulze, E.D., Braatz, S., Grassi, G., Federici, S., 2007b. Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC. Environmental Research Letters 2.

Murty, D., Kirschbaum, M.U.F., McMurtrie, R.E., McGilvray, A., 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? a review of the literature. Global Change Biology 8, 105-123.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., Barbosa, R.I., Keizer, E.W.H., 2008. Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories. Forest Ecology and Management 256, 1853-1867.

Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J., Murray, B.C., 2008. Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods. Environmental Research Letters 3.

Ott, H.E., Sterk, W., Watanabe, R., 2008. The Bali roadmap: new horizons for global climate policy. Climate policy 8, 91-95.

Penman J., M., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F., 2003. Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types. In. The Institute for Global Environmental Strategies for the IPCC and The Intergovernmental Panel on Climate Change., Hayama, Kanagawa, Japan., p. 32 pp.

Potvin, C., Bovarnick, A., 2008. Reducing Emissions from Deforestation and Forest Degradation in Developing Countries: Key Actors, Negotiations and Actions. Carbon & Climate Law Review 3.

Potvin, C., Gotelli, N.J., 2008. Biodiversity enhances individual performance but does not affect survivorship in tropical trees. Ecol. Lett. 11, 217-223.

Potvin, C., Guay, B., Petroni, L., 2008. Is reducing emissions from deforestation financially feasible? A Panamamian case study. Climate Policy 8, 23-40.

Potvin, C., Whidden, E., Moore, T., 2004. A case study of carbon pools under three different land-uses in Panama. Climatic Change 67, 291-307.

Putz, F.E., Zuidema, P.A., Pinard, M.A., Boot, R.G.A., Sayer, J.A., Sheil, D., Sist, P., Elias, Vanclay, J.K., 2008. Improved tropical forest management for carbon retention. PLoS Biology 6, 1368-1369.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., Houghton, R.A., 2007. Challenges to estimating carbon emissions from deforestation. Global Change Biology 13, 51-66.

Sasaki, N. and Putz, F.E. (2009) Critical need for new definitions of forest and forest degradation in global climate change agreements. Conservation Letters 2, 226–232.

Schroeder, P., 1994. Carbon Storage Benefits of Agroforestry Systems. Agroforestry Systems 27, 89-97.

Schwendenmann, L., Pendall, E., 2006. Effects of forest conversion into grassland on soil aggregate structure and carbon storage in Panama: evidence from soil carbon fractionation and stable isotopes. Plant Soil 288, 217-232.

Souza Jr, C.M., Roberts, D.A., Monteiro, A., 2005. Multitemporal Analysis of Degraded Forests in the Southern Brazilian Amazon. Earth Interactions 9, 1-25.

Streck, C., Scholz, S.M., 2006. The role of forests in global climate change: whence we come and where we go. International Affairs 82, 861-879.

Tschakert, P., Coomes, O.T., Potvin, C., 2007. Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama. Ecological Economics 60, 807-820.

UNFCCC 2005. Reducing emissions from deforestation in developing countries: approaches to stimulate action. URL: FCCC/CP/2005/Misc.1. http://unfccc.int/resource/docs/2005/cop11/eng/misc01.pdf Accessed on 11 March 2008.

UNFCCC 2007. Reducing emissions from deforestation in developing countries: approaches to stimulate action. FCCC/SBSTA/2007/L.23/Add.1/Rev.1 URL: http://unfccc.int/resource/docs/2007/sbsta/eng/l23a01r01.pdf Accessed 11 March 2008

UNFCCC 2008. Reducing emissions from deforestation in developing countries: approaches to stimulate action. FCCC/SBSTA/2008/L.23 URL: http://unfccc.int/resource/docs/2008/sbsta/eng/l23.pdf Accessed 26th December 2008

UNFCCC, 2009a. Report on the expert meeting on methodological issues relating to reference emission levels and reference levels. FCCC/SBSTA/2009/2, Subsidiary Body for Scientific and Technological Advice, Thirtieth session, Bonn, 1-10 June 2009. URL: http://unfccc.int/resource/docs/2009/sbsta/eng/02.pdf

UNFCCC, 2009b. Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks. FCCC/TP/2009/1 URL: http://unfccc.int/resource/docs/2009/tp/01.pdf

UNFCCC, 2009c. Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. Draft Decision/CP.15 Advanced Unedited Version URL: http://unfccc.int/files/na/application/pdf/cop15_ddc_auv.pdf

Urquiza-Haas, T., Dolman, P.M., Peres, C.A., 2007. Regional scale variation in forest structure and biomass in the Yucatan Peninsula, Mexico: Effects of forest disturbance. Forest Ecology and Management 247, 80-90.

Wright, J., Samaniego, M. (2008) Historical, demographic and economic correlates of land use change in the Republic of Panama. Ecology and Society 13, 17.

TABLES AND FIGURES

Table 1. Transition probability matrix for the Markov model of land use change.

		1992				
		Mature forest	**Secondary forest**	**Fallow**	**Agriculture**	**Other**
2000	**Mature forest**	0.9709	0.0211	0.0088	0.0006	0.0068
	Secondary forest	0.0099	0.9163	0.0480	0.0027	0.0040
	Fallow	0.0086	0.0425	0.8791	0.0661	0.0062
	Agriculture	0.0099	0.0198	0.0601	0.9295	0.0080
	Other	0.0007	0.0002	0.0040	0.0011	0.9751

Table 2. Summary of data used in the model.

Land-use Class		Description	Partitioning of the deforested land	Standing carbon stock (tC ha^{-1})	Rate of C accumulation (tC ha^{-1} yr^{-1})	Sources
Mature forest		All forests with more than 80% tree cover and plantations	-	Five estimates (Table 3)	4.3	FRA (2005)
Secondary forest		Previously cleared and degraded forest having between 60% and 80% tree cover	0.312	80.4	3.4	FRA (2005)
				fct†	fct†	Alves *et al*. (1997) Brown & Lugo (1982) Potvin and Gotelli (2008)
Fallow		Vegetation following agricultural land abandonment or slash and burn cultivation with less than five years old	0.307	35.4	-	FRA (2005) Tschakert *et al.* (2007)
Agriculture	Annual crop	Crops where the vegetation is collected every year	0.353 (0.246)*	-	-	
	Pasture	Including managed and unmanaged pasture for cattle	0.353 (0.688)*	4.2	-	Kirby & Potvin (2007)
	Permanent crop	Including cocoa, coffee, banana plantations	0.353 (0.066)*	50.0	10.0	IPCC (2003) Schroeder (1994)
Other		Urban areas, inland water, and lowland vegetation liable to flooding	0.028	-	-	

† The function used to calculate the standing stock of the secondary forest was $Csf = Cveg / (1+e^{1.7-0.105*(t)})$ where t is time in years $Cveg$ is the standing stock in mature forest, and Csf the standing stock in secondary forest. The reverting rate was calculated as $\Delta Csf = f(t) - f(t-1)$.

* The fraction of agricultural land in annual crop, pasture, and permanent crop were obtained from the VI Agricultural Census in Contraloría (2001).

Table 3. Characteristics specific to the five estimates of biomass carbon density for the Moist Tropical Forests of Panama used in the sensitivity analysis to the land-use change emissions model.

Source of the estimate	Site	Measurements for AGB§	Plot size (ha)	Number of plots	Description of forest	Estimate (t C/ha)	Model name	Model type/characteristics
Kirby and Potvin (2007)	Ipeti-Embera	All trees ≥ 10 cm DBH†	0.07	32	Old-growth, managed by local community	245	Brown (1997)	Allometric model linking DBH to AGB. This estimate was produced using the large-tree correction proposed by Brown (1997), but without the correction for species-specific WD¶. (See Kirby and Potvin 2007: Appendix A, for further discussion).
Kirby and Potvin (2007)	Ipeti-Embera	All trees ≥ 10 cm DBH†	0.07	32	Idem	169.1	Chave et al. (2004)	Allometric model linking DBH to AGB. Model provides conservative estimates of large tree AGB relative to Brown (1997).This estimate was produced without correcting model for species-specific WD¶ (Chave et al. 2004).
Chave et al. (2004)	Panama Canal Watershed	All trees ≥ 1 cm DBH†	50	1	Late-secondary and primary forests	138.5	Chave et al. (2004)	idem
FRA (2005)	Eastern Panama	All trees with variable minimum DBH†	NA*	NA	NA	130.2	Brown (1997)	BEF‡ to convert commercial volume estimates to biomass carbon density (t/ha).
IPCC	Global estimate	NA	NA	NA	NA	108.5	NA	NA

§ AGB=Above-ground live biomass; ¶ WD=Wood density ‡ BEF= Biomass expansion factor
† DBH=Diameter at breast height; * NA= Not available

Table 4. Total emission reductions comparison for five Moist Tropical FCD estimates in Panama, assuming a 10% reduction of deforestation over an eight-year period and break-even points per ton of CO_{2e}. The overall cost for avoiding deforestation was calculated in function of the area protected, using a net present value of $917.31 on a *per ha* basis (Potvin et al., 2008).

Estimate for the Moist Tropical Forest	**Allometric model**	**Aboveground tree carbon stock** (in tons/ha)	**Total Emission reductions** (in Mtons of CO2e)	**Break-even point** (in US$ per ton of CO_2e)
Kirby & Potvin (2007)	Brown (1997)	245.0	10.6	$6.74
Kirby & Potvin (2007)	Chave et al. (2004)	169.1	7.1	$10.06
Chave et al. (2004)	Chave et al. (2004)	138.5	5.7	$12.55
FRA (2005)	Brown (1997)	130.2	5.3	$13.46
IPCC default value	-	108.5	4.3	$16.58

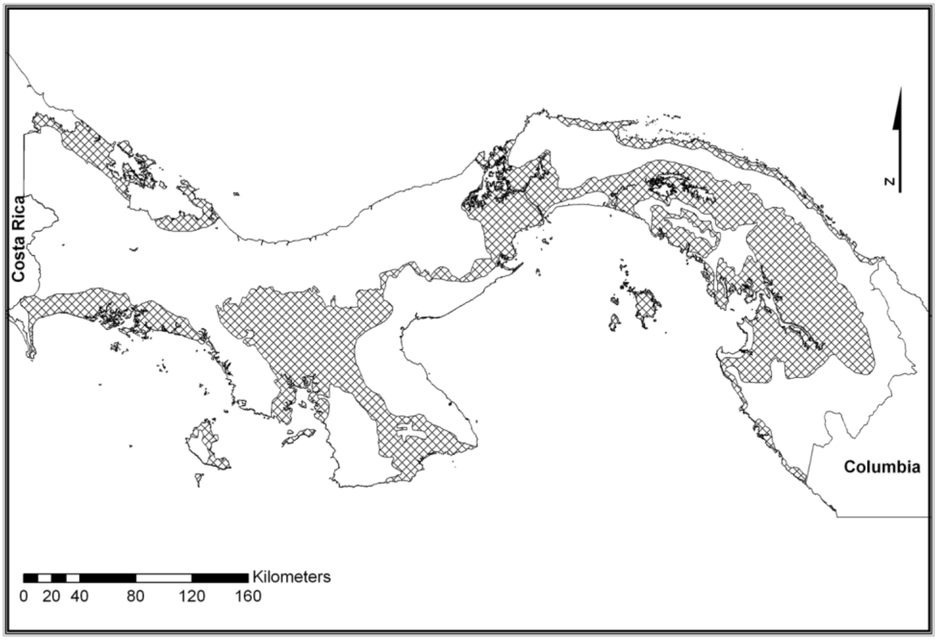

Figure 1. Map representing the extent of the Moist Tropical Forests in Panama according to the Holdridge's life zone classification and covering approximately 3 million hectares.

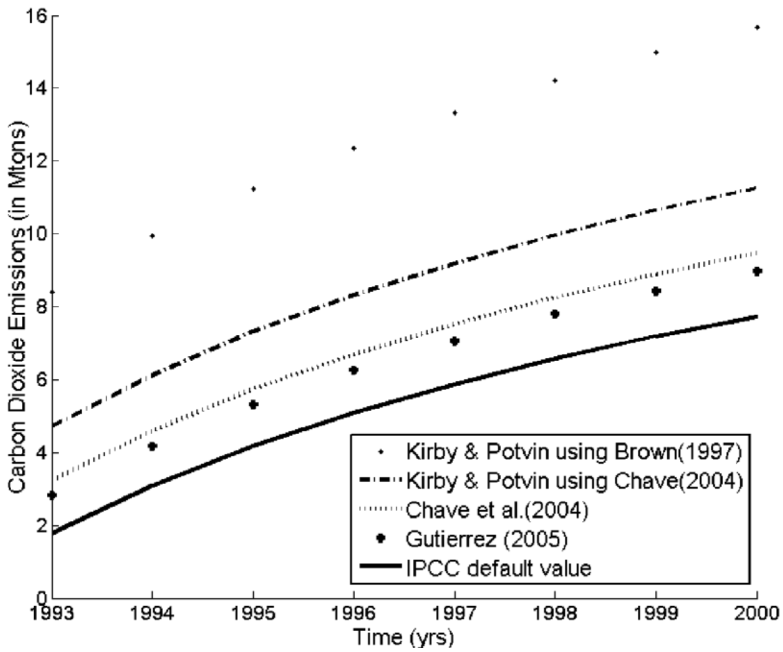

Figure 2. This figure shows the response of the model to changes in forest carbon stock values on estimated annual CO_2 emissions from land-cover change. Five published estimates of above ground tree carbon stocks are compared for the Moist Tropical Forests: 130 tC ha^{-1} (FAO, 2005), 139 t C ha^{-1} (Chave *et al.*, 2004), 109 t C ha^{-1} (IPCC, 2003), and 169 and 245 t C ha^{-1} (Kirby and Potvin, 2007). The last two estimates are based on the same inventory data but use two different allometric models to convert tree measurements to carbon estimates.

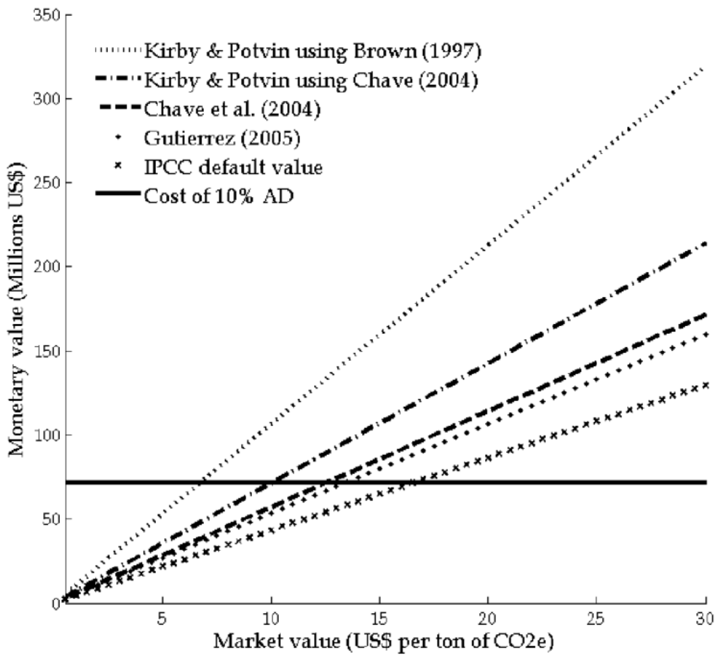

Figure 3. Comparison of the estimated income received to reduce deforestation by 10% annually for 8 years, with an equivalent of 2,170 hectares per year, obtained from five different forest carbon density estimates for the Moist Tropical Forest of Panama. The income is estimated in function of the total emissions reductions (TER) and the market value per ton of CO_2e . The black solid line is the overall cost on a *per hectare* basis estimated from Potvin *et al.* (2008). The break-even points are located where the colored lines cross the black line.

Linking Statement 2

While in chapter 1 the emphasis was restricted to forest carbon density and its impacts on an economic standpoint, in Chapter 2 I provide a full diagnosis of the main sources of error associated with estimates of emissions from deforestation and forest degradation using available data in Panama. I also analyze the overall uncertainty associated with the emissions reduction obtained by different hypothetical land-use scenarios including business as usual.

CHAPTER 2:

Diagnosing the Uncertainty and Detectability of Emission Reductions for REDD+ under Current Capabilities: an Example for Panama

Status: Pelletier, J., Ramankutty, N., Potvin, C. (2011) Diagnosing the uncertainty and detectability of emission reductions for REDD+ under current capabilities: an example for Panama. Environmental Research Letters 6, 024005.

ABSTRACT

In preparation to the deployment of a new mechanism that could address as much as one fifth of global greenhouse gas emissions by Reducing Emissions from Deforestation and forest Degradation (REDD+), important work on methodological issues is still needed to secure the capacity to produce measurable, reportable, and verifiable emissions reductions from REDD+ in developing countries. To contribute to this effort we have diagnosed the main sources of uncertainty in the quantification of emission from deforestation for Panama, one of the first countries to be supported by the Forest Carbon Partnership Facility of the World Bank and by UN-REDD. Performing sensitivity analyses using a land-cover change emissions model, we identified forest carbon stocks and the quality of land-cover maps as the key parameters influencing model uncertainty. The time interval between two land-cover assessments, carbon density in fallow and secondary forest, as well as the accuracy of land-cover classifications also affect our ability to produce accurate estimates. Further, we used the model to compare emission reductions from five different deforestation reduction scenarios drawn from governmental input. Only the scenario simulating a reduction in deforestation by half succeeds in crossing outside the confidence bounds surrounding the baseline emission obtained from the uncertainty analysis. These results suggest that with current data, real emission reductions in developing countries could be obscured by their associated uncertainties. Ways of addressing the key sources of error are proposed to developing countries involved in REDD+ to improve the accuracy of their estimates in the future. These new considerations confirm the importance of current efforts to establish forest monitoring systems and ameliorate capabilities for REDD+ in developing countries.

INTRODUCTION

An agreement for the inclusion of a mechanism to enable developing countries to receive financial compensation for Reducing Emissions from Deforestation and forest Degradation (REDD+) has been achieved at the sixteenth Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Cancun, Mexico in 2010. While previous approaches aiming to curb global deforestation have not been successful (FAO, 2006), REDD+ is considered by many as an unprecedented opportunity to mobilize the global collaborative efforts and resources necessary to acknowledge the ecosystem services rendered by tropical forests (Chomitz, 2007; Ebeling and Yasue, 2008) while promoting sustainable livelihood and development (Bellassen and Gitz, 2008; Hall, 2008), and protecting biodiversity (Gullison et al., 2007; Laurance, 2007).

Methodological guidance for REDD+, adopted in Copenhagen in December 2009, calls for developing countries to establish national forest monitoring systems that can provide transparent, consistent, and as far as possible accurate estimates that reduce uncertainties, taking into account national capabilities and capacities (UNFCCC, 2009b). Indeed, the success of a REDD+ mechanism depends upon countries' ability to provide measurable, reportable, and verifiable emission reductions.

Accurate measurements of emission reductions are desirable from the view point of the climate and as a guarantee against introduction of "hot air" in the climate regime (Angelsen, 2008; Karsenty, 2008). It is also desirable from an economic stand point as it is expected that emission reductions in developing countries will be compensated for by developed countries whether under a market or a fund. Yet, high uncertainties in input data may seriously undermine the credibility of emission estimates and therefore of REDD+ as a mitigation option (Grassi et al., 2008).

Recent research has been conducted on the issue of uncertainty in quantifying emission reductions for REDD+, but it has dealt primarily with uncertainty at the project scale (Fearnside, 2001), with theoretical estimation of few sources of error (Persson and Azar, 2007) or with approaches to deal with uncertainty (Grassi et al., 2008). Other studies give a comprehensive and complete review of uncertainty in emissions estimates; however, they were conducted in developed countries for example as part of greenhouse gas inventories (Bottcher et al., 2008; Monni et al., 2007; Nahorski and Jeda, 2007; Peltoniemi et al., 2006; Rypdal and Winiwarter, 2001; Smith and Heath, 2001). While the studies in developed countries are instructive and provide important references, they do not adequately represent current data availability in developing countries willing to engage in REDD+.

A technical paper published by the UNFCCC, on the cost of implementing methodologies and monitoring systems required for estimating emissions from deforestation and forest degradation assesses the gaps in current monitoring capabilities in developing countries (UNFCCC, 2009a). The publication concludes that the majority of non-Annex I countries have limited capacity in providing complete and accurate estimates of GHG emissions and removals from forests (UNFCCC, 2009a). Only 3 out of 99 tropical countries currently have the capacity considered "very good" for both forest area change and for forest inventories (Herold, July 2009).

The GOFC-GOLD project, which provides the most comprehensive methodological guidance for developing countries involved in REDD+, discusses ways to measure emissions adequately and to deal with uncertainty (GOFC-GOLD, 2010). However, while the documents cited above provide important considerations on the issue of uncertainty, they do not offer a comprehensive and systematic analysis of uncertainties in input data and its implications for REDD+ based on current data available to developing countries.

Using Panama as an example, this study is the first effort to provide a diagnosis of the key sources of error on a national scale using the information available in a developing country. By combining the uncertainties with the Monte Carlo approach, we provide a clear illustration of the implications of uncertainty for REDD+. The study focus on providing tools to countries involved in REDD activities to improve the accuracy of their forest-related emissions and removals in the future. Arising from this analysis, we propose cost-effective ways to reduce error in emission reductions and thus help orient readiness activities.

Panama's national context

Panama is a small country with an area of circa 74,500 km^2 that forms a land bridge between North and South America (ANAM, 2006; ANAM/ITTO, 2003). Panama has a very rich biodiversity with two-thirds of the country falling in the highest and high priority categories for biodiversity conservation (Condit et al., 2001; Myers et al., 2000). In 2000, 45% of the country was forested and experiencing a rate of deforestation estimated at 1.12% per annum, or the equivalent of 41,321 ha for 1992-2000 (figure 1) (ANAM, 2006; ANAM/ITTO, 2003) and 0.36% for 2000-2010 (FRA, 2010). Land-cover change is the primary source of carbon emissions in Panama and represents ~60% of emissions (ANAM, 2000). The main driver of this is agricultural expansion for cattle ranching and subsistence agriculture (Heckadon-Moreno and McKay, 1984). According to the World Bank, Panama is an upper-middle income developing country that suffers from extreme income inequality affecting 40% of its population, with one half of rural residents living below the poverty line (WB, 2007). Panama is one of the first countries to be selected for funding by the Forest Carbon Partnership Facility of the World Bank and the UN-REDD initiative and is currently starting its Readiness phase for REDD+.

METHODS

With the aim of investigating uncertainty in available input data, we first developed a reference emission level (REL) by coupling a Markov-based model of land-cover change with a book-keeping carbon cycle model, a well-characterized land-cover change emission model adapted from Ramankutty *et al.* (2007) [available in the Annex1]. The first-order Markov model was used to determine the land-use dynamics after deforestation. The bookkeeping carbon cycle model served to estimate emissions from land-cover change. The model consists of a linear projection of the annual deforestation area found between 1990 and 2000.

The Markov model was parameterized using two land-cover landsat-based maps (1992 and 2000) produced by ANAM (ANAM/ITTO, 2003). The methodology of image analysis employed and as described by ANAM to create the 2000-2001 map combined non-supervised and supervised classification of the areas of interest. The classification was verified with ground-truthing and was corrected for areas that did not match the classification. The 1992 map was derived from archived images and was verified using available aerial photos (Prieto C., personal communication). These maps are reported to have a 'very high' but un-quantified accuracies (ANAM/ITTO, 2003) and can be visualized online at : http://mapserver.anam.gob.pa/website/coberturaboscosa/viewer.htm. The vector-format of these maps was rasterized at 100-m pixel resolution to fade out possible mis-registration on the overlaid maps. The country was spatially disaggregated into eight life zones. This life zone stratification strategy allowed us to reduce uncertainty for the national emissions estimate, according to validation tests. Land-cover change, including annual deforestation, was evaluated for the eight life zones with spatial analysis of the overlaid maps. Eight contingency tables were built, and transformed into annual transition probability matrices [available in Annex]. Each matrix included five land-cover categories: mature forest, secondary forest, fallow, agriculture, and other. These categories arose from the land-cover classification performed with the ANAM/ITTO project (2003) (see definition in Annex). The matrices were used to simulate land-cover dynamics through time from 2000 until 2030.

The parameters and variables used in the model per life zone are provided in [Annex]. Carbon density information per land-cover was mainly derived from the Panama's national report to the Forest Resource Assessment (FRA) ((Gutierrez, 2005) available online at: http://www.fao.org/forestry/fra/50896/en/pan/), the national greenhouse gases inventory, and expert knowledge. Three pools (Burn, Slash, and Product) were used to account for different timescales of emissions after forest clearing. The model generated annual net emissions from land-cover change per life zone which were summed up to the national amount. However, it does not provide a complete estimate as CO_2 emissions from soils and forest degradation, as well as emissions of non-CO_2 gases have been ignored.

The variance on different input variables and the effect of missing information and assumptions on inputs based on expert knowledge were investigated for this model. As a first step, a sensitivity analysis served to investigate potential sources of error by comparing the result to the REL. Afterwards these different sources of error on the key parameters were combined with a Monte Carlo error propagation analysis to obtain the overall error on the model's output.

The sensitivity analysis was carried out to compare uncertainties stemming from input variables that correspond to the land-cover map quality, the land-cover dynamics, the forest carbon density, and the fate of carbon after deforestation. The effect of varying one input variable at a time is compared to the REL in order to evaluate the impact on emissions estimated for land-cover change and to identify key parameters for uncertainty.

For the Monte Carlo uncertainty propagation, we accessed the inventory data that were used in the FRA for mature forest, secondary forest, and fallow carbon density and corrected accordingly to ensure coherence between the data reported in FRA (Gutierrez, 2005) and this analysis. This information allowed us to derive probability distribution for each key parameter per life zone (Granger Morgan and Henrion, 1990; IPCC, 2000). Further information on the data used and its probability distribution is provided in [Annex]. We simulated the model per life zone by running 10,000 iterations using a Simple Random Sampling (SRS) of parameter values within defined ranges. In other studies, correlations between parameters emerged as influential component of uncertainty (Peltoniemi et al., 2006; Smith and Heath, 2001). For this model, key parameters and input variables are assumed to be correlated through time but independent between the different iterations of the Monte Carlo analysis. We evaluated the 95% confidence intervals per life zone and compared it to the mean generated with the Monte Carlo analysis. To propagate the error on the overall results, we added the mean and the variance obtained for each life zone and calculated the total mean and the 95% confidence intervals (Granger Morgan and Henrion, 1990; Hammonds et al., 1994).

This research also tested different scenarios to reduce emissions from deforestation, in collaboration with the National Environment Authority (ANAM). The five scenarios tested come from ideas and discussions with civil servants in Panama's government and are distinguished by the area chosen in which to pursue a deforestation reduction strategy [See scenarios description in Table 4 and maps in Annex]. Two scenarios (**SINAP** with 54 protected areas and **CBMAP II** with 14 protected areas) reflect the governmental input received. Other scenarios served at testing the emission reductions possible by 1) applying the same surface area as the CBMAP II scenario in deforestation hotspots (**Palo**

Seco & Darién), 2) probing a community-based approach in the same area (**Replication of Ipetí-Emberá**), and 3) a 50% deforestation reduction (**Stern Review**).

RESULTS

Sensitivity analysis

Land cover map quality

Two land-cover maps ostensibly for 1992 and 2000, made available by the National Environment Authority of Panama (ANAM), constituted the most recent and officially validated land cover analysis for Panama at the time of this study (ANAM/ITTO, 2003). However, the mosaics of Landsat images that constitute these maps are not exactly from the years specified. For the 1992 map, images ranged from 1988 to 1992 and for the 2000 map images were from 1998 to 2001 (Table 1). It should be further noted that the 1992 map was made in 2002 using archived images and that as many as five years separate the images used to create the map; the choice of images was most likely based on the best data available in moderate resolution imagery for this period due to the difficulty in finding cloud-free images.

The fact that a map created for one year is based on images from different years might generate error in the quantification of emissions from land-cover change and has the potential to create an uncertain history of such emissions. For the same total area deforested, annual emission estimates will be affected if the change takes place over a ten-year period rather than an eight-year period. Since the time interval between two images of the same area is generally greater than eight years, a 10-year difference between the maps was used to define the REL in order to have a conservative representation of emissions by avoiding the risk of overestimating emissions from land-cover change. We then compared the effect of 9-year and 8-year time span between the two land-cover maps instead of ten years used in the REL and obtained an average difference in emissions of 15.6% and 35.2% respectively (figure 2). These differences in emissions stem from (i) deforestation area and (ii) land-cover dynamics after deforestation. On the one hand, annual deforestation area is a function of the total area deforested and the time interval between two maps. On the other hand, land cover dynamics after deforestation is expressed by the transition probabilities and involves secondary forest and fallow regrowth and clearing. If the time interval between two images is shorter the transition probabilities from one land-use to another becomes higher. We estimated the portion of the error due to time interval between the two land-cover maps by using as deforestation area the value used in the REL and therefore isolating the effect of land-cover dynamics on the error. We obtained 8.2% and 16.5 % respectively, which corresponds to about half of the total error evaluated for the effect of the uncertain time span between the two maps (figure 2). We can therefore observe that both the deforested area and transitions to other land covers associated with the land-cover dynamics have an impact on emission estimates.

Moreover, a land-cover classification accuracy assessment was not performed or provided for these maps. An accuracy assessment is a fundamental part of any thematic mapping exercise as it serves to determine to what degree the situation depicted on the thematic map is coherent based on the reality on the ground (Foody, 2002). As land-cover misclassification could possibly affect the determination of deforested areas, we tested for possible error by assuming different levels of Coefficient of Variation (C.V.) on the deforested areas accounted for. The estimated emissions varied between 2.2% and 19.1% from the REL, for CV changes in deforested area ranging from 1% to 15% (figures not shown). The upper limit tested (15%) was derived based on the standard accepted classification accuracy level (85% accuracy level) (Foody, 2002).

Snapshot effect

We also accounted for what we have called the *snapshot effect*, or the fact that we only possess land-cover information from two points in time, and consequently have only partial knowledge of land-cover dynamics between the two dates. We tested the consequence of this lack of knowledge on emission estimates from land-cover change. One possible occurrence during this period is a greater frequency of the agriculture-fallow cycle than observed in the maps. Effectively, fallow in Panama is defined as "*successional vegetation that is less than five years old following agriculture*" (ANAM/ITTO, 2003). In the absence of frequent satellite imagery, it means that more fallow might in fact have been cleared during the 1990-2000 period than currently seen on the maps. Assuming that the fallow land-cover is effectively less than five years of age, it can be assumed that at the end of a five-year period all fallow land existing at the beginning of the time period should have returned to agriculture. For our ten-year timespan, it is possible that all fallow land had gone through one (or more) additional agriculture-fallow cycles than we are currently able to observe from these maps. This would have a negative impact on carbon accumulation in fallow. We therefore tested for a faster agriculture-fallow cycle, making sure that we obtained similar final conditions in 2000 as the ones seen on the 2000 map (the model's simulation starts in 1990). To do so, we increased the transition from fallow to agriculture and from agriculture to fallow in order to shorten the agriculture-fallow cycle and we estimated that emissions would be, on average, 19.3 % greater than the REL. The high sensitivity of emissions to this parameter is explained by the large areas covered by agriculture and fallow land. An important part of the land-cover dynamic is likely to be obscured when the time interval between two land-cover maps is larger than the timescale of the clearing-fallow cycle. This, in turn, would affect the quantification of GHG emissions from land-cover change.

Carbon stock data

Fallow land covers a significant portion of Panama, but it is relatively understudied in terms of carbon density as few inventories have been performed. The carbon stock in fallow land should depend principally on different factors such as the land-use history, including the intensity and duration of cultivation, occurrence of fires, age of fallow, as well as the proximity to forests or seed banks. However, for vegetation less than five years old, the variance in carbon stocks should not be as high as the one found for mature forest. We tested the sensitivity of land-cover emissions to carbon stock for fallow land and found a variation of 22.4% around the REL (figure 3a).

For mature forest carbon stocks, we used the various forest inventory carbon stock estimates gathered for the Forest Resources Assessment (2005) of Panama [Annex]. We selected the lowest and highest values of mature forest carbon stock estimates for each life zone. Our results show that the amount of mature forest carbon stock is the most sensitive parameter in the model, as high and low initial values caused a 54.5% variation in the estimate of emissions from land-cover change.

The fate of carbon after deforestation

The model assumes three emissions timescales after forest is cleared for the following carbon pools: 1) carbon released instantaneously through burning of plant material (burn pool), 2) left on site as slash that decomposes through time (slash pool), or 3) stored in wood products and released over a long time period (product pool). We examined the sensitivity of changing the fraction dedicated to each carbon pool compared to the REL according to the literature for Panama (Gutierrez, 1999) and studies for the Brazilian Amazon (Houghton et al., 2000; Ramankutty et al., 2007). The parameters used to determine the fate of carbon after deforestation had only a slight effect on the distribution of emissions through time (figure 3b). This result might be different if other non-CO_2 greenhouse gases (e.g. CH_4, NO_2) were accounted for.

Uncertainty analysis

The sensitivity analysis discussed above allowed us to identify key input variables. We next used a Monte Carlo numerical uncertainty analysis to propagate errors coming from the uncertainty of these variables into the model. With the exception of map accuracy assessment tests, all the key variables identified were included in the uncertainty propagation expressed by uniform, normal, lognormal and gamma probability distribution functions detailed in [Annex]. The map classification accuracy assessment was left out of the uncertainty analysis because the sensitivity tests were performed based on information from the literature rather than from empirical data for Panama.

In figure 4, we can observe the upper and lower confidence limits for each life zone separately. The results from this simulation show that emissions from land-cover change and its associated uncertainty is geographically concentrated in three life zones where deforestation is an active process, with Moist Tropical forest largely dominating the trend. Moist Tropical forests are located at low altitudes where land is sought out for colonization. They cover the largest extent of the national territory and host about half of the national annual deforestation. The area also has had the highest number of forest inventories performed (n=33) and is far better studied than other areas. These inventories were used to obtain a mean value and a standard deviation for the Monte Carlo analysis. Unfortunately, data availability does not warrant quality; systematic sampling error (lack of representativeness), and random error (plot size and number of data points) can partially explain the differences observed between the estimates. In fact, the different carbon stock estimates come from heterogeneous sources with different methodologies, not performed for carbon monitoring purposes. Yet part of the uncertainty is also expected to come from the high spatial variability of forest carbon stocks.

Finally, when propagating error to the total CO_2 emissions from land-cover change for the entire country, the overall model output uncertainty reaches an average of ± 43.5% between the 95% confidence intervals and the mean generated from the Monte Carlo simulations.

Scenario analysis

Next, we compared the emission reductions achieved by five different deforestation reduction scenarios, with two of them reflecting government input on priorities for national REDD+ activities (Panama's Atlantic Mesoamerican Biological Corridor (CBMAP II) and the National Protected Area System (SINAP). The government has shown interest in reducing deforestation principally in protected areas (see Table 2 for scenario description). Roughly 34% of Panama's territory is partitioned into 65 protected areas (ANAM, 2006). According to our observations between 1992 and 2000, more than 15% of the annual deforestation was conducted inside protected areas. While more recent investments in the SINAP might have reduced deforestation to some extent, various protected areas are at risk of encroachment and boundaries have not yet been stabilized (Oestreicher et al., 2009). Table 3 reports the annual deforestation reduction and its effects on emissions compared to the REL. The CBMAP II scenario achieves only 2.2% reduction in annual deforestation, indicating a relatively low impact on land-cover change rates in most of the 14 protected. For the same surface area (~600,000 ha), if the CBMAP II project was taking place in eastern Panama (Darién region) with the Palo Seco Forest Reserve, nine times greater reduction in emissions could be achieved. As logically expected, more emission reductions can be achieved in areas experiencing more deforestation.

Combining scenarios and uncertainty

The most striking result from this analysis is that when comparing the five scenarios with the confidence bounds analyzed through the Monte Carlo uncertainty analysis (figure 5), none of the scenarios tested achieve emission reductions outside the error margins except for the Stern Review scenario. Even the Stern Review scenario, where Panama would reduce deforestation by 50%, only crosses the confidence limit in 2022 (deforestation reduction is conducted progressively as described in Table 2). This leads to the notion that overall uncertainty in the quantification of emissions from land-cover change could impede the detection of real emission reductions from REDD+.

DISCUSSION AND CONCLUSIONS

Following the UNFCCC decision on methodological guidance for REDD+ (UNFCCC, 2009b), developing countries are requested to establish robust and transparent national forest monitoring systems for REDD+. In this context, our study brings much needed insight regarding the main sources of error in emission estimates from REDD+ in consideration of current data availability and provides guidance to developing countries engaged in REDD+ to focus their efforts in collecting information that contribute the most to reducing uncertainty in a cost-effective manner.

At the outset, Table 4 synthesizes the key sources of uncertainty in the quantification of emissions from land-cover change in Panama, with an explanation of the main causes of this error. The primary source of error is in mature forest carbon stock estimates. This is in line with research in the Brazilian Amazon where estimates span wide ranges (Houghton, 2005; Houghton et al., 2001) and hamper accurate emission estimates (Houghton et al., 2000). The combination of errors drawn from allometric equations and sampling can be as large as 20 to 50% of the aboveground biomass estimate (Chave et al., 2004; Keller et al., 2001; Persson and Azar, 2007). Other factors which contribute similarly to uncertainty in land-cover change emissions include historical map quality, land-cover classification accuracy, the time interval between two land-cover assessments, and the fallow C.

As recognized by recent reports, very few developing countries either measure soil carbon stocks on a regular basis or report data on soil carbon (Herold, July 2009; UNFCCC, 2009a). For this same reason, soil C was ignored in this analysis as Panama has primarily been using default values for its GHG inventory. This study also did not address the issue of forest degradation because of the lack of information on the dynamics of this land-cover process which is induced by the long time intervals between the two land-cover assessments. Ignoring these two contributors can lead to an underestimation of emissions. This underlines the pressing necessity for a global expansion of research on forest degradation processes and a prioritization of long term studies on soil C to improve our knowledge, and increase the completeness of emissions accounting mainly in countries where forest peatlands are present or when deforestation is conducted for the benefit of annual crops.

Priorities for reducing uncertainty

The present methodological exercise highlights important practical lessons that can be used by countries willing to engage in REDD+ to improve the precision and accuracy of their national baseline. First of all, not surprisingly, identifying and targeting carbon stock sampling in deforestation hotspots will have the largest impact on reducing uncertainty and possibly reducing monitoring costs. Research in the Brazilian "Arc of deforestation", supports this assertion as trees that were shorter and of lower wood density than in other areas were found to be deforested, leading to a revision of emission estimates (Nogueira et al., 2007; Nogueira et al., 2008). In Panama, most of the overall uncertainty in emissions arises from the Moist Tropical forest.

We observed with the Monte Carlo analysis that both random errors, which affect precision, and systematic errors (or biases), which affect accuracy, need to be addressed to reduce uncertainty (Grassi et al., 2008). For the case of mature forest carbon density, adopting national standard inventory methods would improve accuracy and therefore allow to partition the uncertainty between natural variability and errors in measurement (Chave et al., 2004). On the other hand, for fallow C, augmenting replication would increase precision and therefore reduce the overall uncertainty.

This study shows that mosaicking multi-year imagery and long time-intervals or a snapshot effect generates substantial errors in the quantification of emissions from land-cover change. These issues are not unique to Panama but are rather ubiquitous in national and even project-level land-cover studies worldwide. These issues are common and they present important challenges to tropical countries as few of them can access the moderate resolution imagery needed to capture changes in forest cover at meaningful scales to commensurate small-holder deforestation and diffuse degradation processes. Long revisiting time and frequent cloud cover due to evapo-transpiration over tropical forests or smoke from forest clearing signify that moderate resolution imagery might only be available once every few years. One remedy has been to use low-resolution imagery (e.g. MODIS or AVHRR), but doing so comes at the expense of producing an accurate picture of land-cover processes and associated emission estimates.

In fact, historical maps made of archived images from different years should be used only with caution and conservatively, in order not to overestimate emissions. This could be done by adjusting the rates of land-cover change for the different time intervals between the individual images of two assessments in a spatially-explicit manner (Olander et al., 2008) or to assume the largest interval applied to the entire map. For instance, to avoid overestimating its baseline, Panama would be required to account for a 10-year minimum difference between its two land-use assessments of 1992 and 2000, instead of the eight years. What's more, when historical maps are made from archived images, fine-resolution imagery (aerial photos) and ground-based data may not be available to provide suitable accuracy assessments for a given period (Foody, 2009). If we were to suggest that only more recent land-cover assessments be used from now on to reduce uncertainty, ignoring land-cover history and past deforestation might underestimate present-day emissions (Caspersen et al., 2000; Fearnside, 2000; Houghton, 2003; Kauffman et al., 2009; Ramankutty et al., 2007). On the other hand, policy frameworks could potentially use "committed emissions" rather than "actual emissions", in which case land-cover change history would not matter (Fearnside, 1997, 2000). Note that more recent and future assessments may substantially reduce this source of uncertainty through better accuracy, systematic collection and analysis of images captured from ground-based stations covering the tropics, and with the availability of radar and lidar imagery (Herold, July 2009). In all cases an accuracy assessment of the land-cover classification map should be performed using transparent methodologies and reporting methods, as the value of a map is clearly a function of the accuracy of the classification (Foody, 2002).

In addition, multi-temporal land-cover assessments at smaller than 8 to 10 year time intervals could significantly reduce uncertainties on land cover and forest change processes (DeFries et al., 2007; GOFC-GOLD, 2010) and improve knowledge of land-cover dynamics. Processes such as forest degradation, agriculture-fallow cycles, regrowth, succession, and important events (fire, hurricanes, and landslides) could therefore be tracked through time improving the understanding of the spatial distribution of carbon stock over large extents. The current partial understanding of the dynamics and the spatial distribution of carbon stocks in the tropics is constraining the analysis of emissions from land-cover change to high levels of uncertainty (Houghton, 2005, 2010; Ramankutty et al., 2007). For instance, studies show that annual monitoring would be desirable and potentially necessary for the detection of forest degradation (Asner et al., 2004a; Asner et al., 2004b; Souza Jr et al., 2005a; Souza Jr et al., 2005b).

The snapshot effect makes it hard to track the cleared land, a central requirement to be able to separate gross emissions from net emissions. This study calculates net forest-related emissions because the model allowed them to be offset using carbon sequestration from forest re-growth or plantations. However, REDD is likely to require gross reductions in GHG emissions from deforestation and forest degradation. A temporal resolution of a decade or larger necessarily leads to a fuzzy estimation located in-between net and gross emissions because several land-cover processes cannot be tracked appropriately. The difficulty to distinguish between gross and net emissions increases as the temporal resolution diminishes or as larger timesteps are used.

Furthermore, we identified a challenge for harmonizing land-cover classification definitions and associated carbon flux from land-cover change into a consistent model structure (e.g. definition of secondary/intervened forest). Two options exist for defining these activities under REDD+: (i) attempting to define each individual activity based on a variety of unique criteria, or (ii) using generic definition (e.g. Forest land remaining Forest land) as existing in the IPCC GPG framework (Angelsen et al., 2009). The second option is likely to allow for more consistency if we succeed in improving knowledge of the spatial distribution of carbon stock and use a spatially-explicit modeling approach. Recent research indicates the feasibility of such enterprise (Asner, 2009; Asner et al., 2010). Adopting unique criteria and definitions for each activity will be dependent on the technical capacity to sense and record the change, which will probably progress through time.

Finally, one clear general lesson is that under current capabilities, Panama would most likely produce estimates that are too uncertain to allow a clear detection of emission reductions. When compared to the overall uncertainty obtained from the Monte Carlo analysis, only the Stern Review scenario that simulates halving deforestation in Panama is able to cross the lower confidence limit after 2022. This indicates that much of the deforestation reduction would produce emission reductions that are not distinguishable from errors. So, even if the deforestation reduction is effective, it could be argued that these perceived emission reductions are simply due to errors in estimates. If Panama would enter a performance-based REDD+ mechanism where there would be compensation per ton of CO_2 emissions reduced, high uncertainties around emission reduction estimates would not be to the country's benefit.

Reducing uncertainty: a work in progress

These findings confirm the importance of current efforts to develop forest monitoring systems and capacity-building in the tropics. The process is illustrated by the participation of 37 REDD countries that have entered the readiness mechanism under the Forest Carbon Partnership Facility, where countries are working to produce a REL and a forest monitoring system (FCPF, 2010). Using Panama as an illustration, this research indicates that the acquisition of better data might be essential to produce transparent and accurate estimates as requested in the methodological guidance for REDD+ under the UNFCCC (UNFCCC, 2009b). It is important to emphasize here that efforts to acquire appropriate data can significantly reduce the uncertainty in future estimates of forest-related emissions. Focusing efforts in collecting information where it can contribute the most to reduce uncertainty is likely to be both cost-effective for readiness countries and support the robustness of REDD+ on the long term.

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REFERENCES

ANAM, (2000) Primer Inventario Nacional sobre los Gases a Efecto Invernadero., Primera comunicación Nacional sobre Cambios Climáticos. Autoridad Nacional del Ambiente, Panama, Repúplica de Panamá, p. 18pp.

ANAM, (2006) Indicadores Ambientales de la República de Panamá. Autoridad Nacional del Ambiente, Panamá, República de Panamá.

ANAM/ITTO, (2003) Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. Autoridad Nacional del Ambiente, Panama, Republica de Panama, p. 107 pp.

Angelsen, A. (2008) REDD models and baselines. International Forestry Review 10, 465-475.

Angelsen, A., Brown, S., Loisel, C., Peskett, L., Streck, C., Zarin, D., (2009) Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report. Meridian Institute, p. 116.

Asner, G.P. (2009) Tropical forest carbon assessment: integrating satellite and airborne mapping approaches. Environmental Research Letters 4.

Asner, G.P., Keller, M., Pereira, R., Zweede, J.C., Silva, J.N.M. (2004a) Canopy damage and recovery after selective logging in Amazonia: Field and satellite studies. Ecological Applications 14, S280-S298.

Asner, G.P., Keller, M., Silva, J.N.M. (2004b) Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Global Change Biology 10, 765-783.

Asner, G.P., Powell, G.V.N., Mascaroa, J., Knappa, D.E., Clarka, J.K., Jacobsona, J., Kennedy-Bowdoina, T., Balajia, A., Paez-Acostaa, G., Victoriac, E., Secadad, L., Valquid, M., Hughese, F.R. (2010) High-resolution forest carbon stocks and emissions in the Amazon. Proceedings of the National Academy of Sciences of the United States of America 107, 16738-16742.

Bellassen, V., Gitz, V. (2008) Reducing Emissions from Deforestation and Degradation in Cameroon - Assessing costs and benefits. Ecological Economics 68, 336-344.

Bottcher, H., Freibauer, A., Obersteiner, M., Schulze, E.D. (2008) Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model. Ecological Modelling 213, 45-62.

Caspersen, J.P., Pacala, S.W., Jenkins, J.C., Hurtt, G.C., Moorcroft, P.R., Birdsey, R.A. (2000) Contributions of land-use history to carbon accumulation in US forests. Science 290, 1148-1151.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S., Perez, R. (2004) Error propagation and scaling for tropical forest biomass estimates. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 359, 409-420.

Chomitz, K.M. (2007) At Loggerheads?: Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests. The International Bank for Reconstruction and Development/ The World Bank, Washington, D.C.

Condit, R., Robinson, W.D., Ibanez, R., Aguilar, S., Sanjur, A., Martinez, R., Stallard, R.F., Garcia, T., Angehr, G.R., Petit, L., Wright, S.J., Robinson, T.R., Heckadon, S. (2001) The status of the Panama Canal watershed and its biodiversity at the beginning of the 21st century. Bioscience 51, 389-398.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B., de Souza, C. (2007) Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science & Policy 10, 385-394.

Ebeling, J., Yasue, M. (2008) Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 1917-1924.

FAO, (2006) Forest Resource Assessment. Food and Agriculture Organization, Rome.

FCPF, (2010) General Overview: Forest Carbon Partneship Facility. World Bank, Washington, D.C.

Fearnside, P.M. (1997) Greenhouse gases from deforestation in Brazilian Amazonia: Net committed emissions. Climatic Change 35, 321-360.

Fearnside, P.M. (2000) Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46, 115-158.

Fearnside, P.M. (2001) Saving tropical forests as a global warming countermeasure: an issue that divides the environmental movement. Ecological Economics 39, 167-184.

Foody, G.M. (2002) Status of land cover classification accuracy assessment. Remote Sensing of Environment 80, 185-201.

Foody, G.M. (2009) The impact of imperfect ground reference data on the accuracy of land cover change estimation. International Journal of Remote Sensing 30, 3275-3281.

FRA, (2010) Global Forest Resources Assessment 2010: Main report. Food and Agriculture Organization of the United Nations, Rome, p. 378 pp.

GOFC-GOLD, (2010) A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation, GOFC-GOLD Report version COP16-1. GOFC-GOLD Project Office, Natural Resources Canada, Alberta, Canada.

Granger Morgan, M., Henrion, M. (1990) Uncertainty, A guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. . Cambridge University Press, New York.

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D. (2008) Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates. Environmental Research Letters 3, 035005 (035012pp.).

Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D., Nobre, C. (2007) Tropical Forest and Climate Policy. Science 316, 985-986.

Gutierrez, R., (1999) Inventario Nacional de Gases de Efecto Invernadero para el modulo “Cambio de Uso de la Tierra y Silvicultura”. , in: ANAM (Ed.). República de Panamá, Panamá, p. 115 pp.

Gutierrez, R., (2005) Forest Resource Assessment 2005: Country report Panama. Food and Agriculture Organization-Forest Department, Rome, p. 118p.

Hall, A. (2008) Better RED than dead: paying the people for environmental services in Amazonia. Philosophical Transactions of the Royal Society B-Biological Sciences 363, 1925-1932.

Hammonds, J.S., Hoffman, F.O., Bartell, S.M., (1994) An Introductory Guide to Uncertainty Analysis in Environmental and Health Risk Assessment, in: SENES Oak Ridge, I. (Ed.). Oak Ridge National Laboratory, Oak Ridge, Tennessee, p. 34.

Heckadon-Moreno, S., McKay, A. (1984) Colonización y Destrucción de Bosques en Panamá: Ensayos sobre un grave problema ecológico. . Asociación Panameña de Antropología, República de Panamá.

Herold, M., (July 2009) An assessment of national forest monitoring capabilities in tropical non-Annex I countries: Recommendations for capacity building. Friedrich Schiller University Jena and GOFC-GOLD Land Cover Project Office, p. 61 p.

Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus Series B-Chemical and Physical Meteorology 55, 378-390.

Houghton, R.A. (2005) Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945-958.

Houghton, R.A. (2010) How well do we know the flux of CO2 from land-use change? Tellus Series B Chemical and Physical Meteorology 62, 337-351.

Houghton, R.A., Lawrence, K.T., Hackler, J.L., Brown, S. (2001) The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Global Change Biology 7, 731-746.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H. (2000) Annual fluxes or carbon from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301-304.

IPCC, (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. . IPCC/OECD/IEA/IGES, Hayana, Japan.

Karsenty, A. (2008) The architecture of proposed REDD schemes after Bali: facing critical choice. International Forestry Review 10, 443-457.

Kauffman, J.B., Hugues, R.F., Heider, C. (2009) Carbon pool and biomass dynamics associated with deforestation, land use, and agricultural abandonment in the neotropics. Ecological Applications 19, 1211-1222.

Keller, M., Palace, M., Hurtt, G. (2001) Biomass estimation in the Tapajos National Forest, Brazil: examination of sampling and allometric uncertainties. Forest Ecology and Management 154, 371-382.

Laurance, W.F. (2007) A new initiative to use carbon trading for tropical forest conservation. Biotropica 39, 20-24.

Monni, S., Peltoniemi, M., Palosuo, T., Lehtonen, A., Makipaa, R., Savolainen, I. (2007) Uncertainty of forest carbon stock changes - implications to the total uncertainty of GHG inventory of Finland. Climatic Change 81, 391-413.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J. (2000) Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Nahorski, Z., Jeda, W. (2007) Processing National CO2 Inventory Emissions Data and their Total Uncertainty Estimates. Water, Air, & Soil Pollution: Focus 7, 513-527.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., França, M.B. (2007) Wood density in forests of Brazil's 'arc of deforestation': Implications for biomass and flux of carbon from land-use change in Amazonia. Forest Ecology and Management 248, 119-135.

Nogueira, E.M., Nelson, B.W., Fearnside, P.M., Franca, M.B., de Oliveira, A.C.A. (2008) Tree height in Brazil's 'arc of deforestation': Shorter trees in south and southwest Amazonia imply lower biomass. Forest Ecology and Management 255, 2963-2972.

Oestreicher, J.S., Benessaiah, K., Ruiz-Jaen, M.C., Sloan, S., Turner, K., Pelletier, J., Guay, B., Clark, K.E., Roche, D.G., Meiners, M., Potvin, C. (2009) Avoiding deforestation in Panamanian protected areas: An analysis of protection effectiveness and implications for reducing emissions from deforestation and forest degradation. Global Environmental Change 19, 279-291.

Olander, L.P., Gibbs, H.K., Steininger, M., Swenson, J.J., Murray, B.C. (2008) Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods. Environmental Research Letters 3.

Peltoniemi, M., Palosuo, T., Monni, S., Makipaa, R. (2006) Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation. Forest Ecology and Management 232, 75-85.

Persson, U.M., Azar, C. (2007) Tropical deforestation in a future international climate policy regime- lessons from the Brazilian Amazon. Mitigation and Adaptation Strategies for Global Change 12, 1277-1304.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., Houghton, R.A. (2007) Challenges to estimating carbon emissions from deforestation. Global Change Biology 13, 51-66.

Rypdal, K., Winiwarter, W. (2001) Uncertainties in greenhouse gas emission inventories -- evaluation, comparability and implications. Environmental Science & Policy 4, 107-116.

Smith, J.E., Heath, L.S. (2001) Identifying influences on model uncertainty: An application using a forest carbon budget model. Environmental Management 27, 253-267.

Souza Jr, C.M., Roberts, D.A., Cochrane, M.A. (2005a) Combining spectral and spatial information to map canopy damage from selective logging and forest fires. Remote Sensing of Environment 98, 329-343.

Souza Jr, C.M., Roberts, D.A., Monteiro, A. (2005b) Multitemporal Analysis of Degraded Forests in the Southern Brazilian Amazon. Earth Interactions 9, 1-25.

UNFCCC, (2009a) Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks., FCCC/TP/2009/1.

UNFCCC, (2009b) Methodological guidance for activities relating to reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries, Decision 4/CP.15.

WB, (2007) Rural Productivity Project (PRORURAL), in: Unit, C.A.C.M. (Ed.), Project Appraisal Document to the Republic of Panama. The World Bank, Washington, D.C., p. 77.

TABLES AND FIGURES

Table 1. Satellite images used for the creation of the land cover maps of 1992 and 2000 for Panama.

Area	Date for the 1992 Map	Date for the 2000 Map	Sensor	Path	Row
Canal Watershed	Feb-90	Mar-00	Landsat 5	12	54
Darién	Jun-90	Mar-00	Landsat 5-7	11	54
Azuero	Apr-88	Dec-00 Jun-01	Landsat 5	12	55
Veraguas	Nov-88 Feb-90	May-99 Jan-01	Landsat 5	13	54
Montijo	Feb-90 Feb-90	Feb-00 Feb-01	Landsat 5	13	55
Changuinola	Nov-92	Jan-99 Dec-00	Landsat 5	14	53
Chiriquí-Bocas	Mar-90	Feb-98 Dec-00	Landsat 5	14	54
Kuna Yala	-	Aug-00	Landsat 5	11	53
South-East of Darién	Jun-89	-	Landsat 5	11	55

* Source: ANAM/ITTO (2003) Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. Panama, Republica de Panama, Autoridad Nacional del Ambiente.

Table 2. Description of the scenarios tested with the model.

Reference Emission Level (REL)	▪ REL is used as a baseline to evaluate emission reductions. ▪ It is a projection of the annual deforestation found between 1990 and 2000.
Mesoamerican Biological Corridor of the Atlantic Panama, phase 2 (CBMAP II)	▪ It was adopted in 2007 by the Panamanian government to focus its efforts to biodiversity protection. ▪ It includes 14 protected areas and covers a superficies of 675,775 ha legally of land state-owned/legally controlled by the government. ▪ The deforestation was evaluated between 1990 and 2000 per life zone for the protected areas included in the project (except for Donoso (10,000 ha) that was not yet established). ▪ The scenario included a five-year implementation period (progressive reduction) and assumed that after these five years, annual deforestation will be zero in the area covered by the project.
Palo Seco Forest Reserve & Darien bio-geographical region	▪ Using the same spatial area covered by the CBMAP II project, this scenario included: 1) The Palo Seco Forest Reserve, the protected area included in CBMAP II project with the highest deforestation, 2) The Darien biogeographic region of Panama, where most mature forest clearing between 1990 & 2000 was undergoing. ▪ For the Darien region, 546,253 pixels of one hectare were selected randomly and land use change between 1990 and 2000 was evaluated per life zone. This procedure was repeated 100 times to obtain a mean annual deforestation. ▪ The scenario assumed that 100% of the annual deforestation in the total project area would be curbed.
Deforestation Reduction in the National System of Protected Areas	▪ It includes 54 protected areas under different management categories and covers 2,359,215 ha.[1] ▪ The deforestation was evaluated per life zone for the protected areas. ▪ The scenario included a five-year implementation period (progressive reduction) and assumed that after these five years, annual deforestation will be zero in the area covered by the project.
Replication of Ipetí-Emberá project	▪ Ipetí-Emberá project is a community-based initiative located in Darien bio-geographical region and launched in 2008 to reduce of emissions from deforestation. It is the first REDD project in Panama. This scenario replicates this initiative in 10 communities in high deforestation area. ▪ In Darien region, 682 communities were selected for their proximity to mature forest (less then 2 KM of the village' centroid). We evaluated a buffer area around each community where we evaluated deforestation between 1992 and 2000. The size of the buffer was evaluated in two different ways. For indigenous territories (*Comarca*), we used the population per communities multiply by a mean holding size per person using data from empirical studies executed in the Darien region [2,3]. For communities outside indigenous territories, we used the mean holding area per *corregimiento* and the fraction of producers in each village to determine the village size[4, 5]. ▪ 10 villages were selected randomly and deforestation was evaluated in its surroundings. The procedure was repeated 100 times to obtain a mean annual deforestation for the 10 villages. ▪ This scenario assumes that 100% of the deforestation is curbed.
Stern Review	▪ This scenario was included to evaluate the emission reductions possible if national deforestation rates could be reduced by 50% in consonance with the Stern Review[6], and is used as the upper limit for deforestation reduction. ▪ It includes a progressive implementation over ten years.

[1] This analysis includes all protected areas created before 2000. The area cover by the project was evaluated from GIS data provided by the National Environmental Authority of Panama.
[2] Tschakert P, Coomes OT, & Potvin C (2007) Ecological Economics 60, 807-820.
[3] Sloan S (2008) Global Environmental Change-Human and Policy Dimensions 18, 425-441.
[4] Contraloría General de la República (2001) VI Censo Agropecuario. Dirección de Estadística y Censo, República de Panamá.

[5] Contraloría General de la República (2001) Censo Población y Viviendas 2000. Dirección de Estadística y Censo, República de Panamá.

[6] Stern N (2006)

Table 3. Mean annual emissions reductions from the different deforestation reduction scenarios tested against the reference emission level (REL).

	Annual deforestation reduction (ha)	in %	Mean annual emission reductions from 2010 to 2030 (in Mtons of CO_2/yr)
Replication of Ipetí-Emberá (10)	235.2	0.7	0.02
CBMAP II	747.4	2.2	0.30
SINAP	5965.9	17.4	2.48
Palo Seco + Darien	6443.4	18.7	2.66
Stern Review	17184.7	50	6.03

Table 4. Key sources of uncertainty and their associated difference with the REL.

Sources of error	***%***	***Explanation***
Mature forest C density	**54.5**	- No standardized methodology and error-prone allometric equations or biomass emission factors
Deforested area	**2.2 to 19.1**	- Error in land-cover classification/Lack of classification accuracy assessment
Snapshot effect	**19.3**	- Long time interval between two maps/ Lack of knowledge on land-cover dynamics
Land-cover map quality (9-yr and 8-yr)	**15.6 to 35.2**	- Map based on a mosaic of satellite images from very different years - Low availability of usable satellite imagery (Cloud cover, Long revisiting time, Seasonality) - Coarse resolution imagery (e.g. MODIS or AVHRR) with more frequent revisit times would not produce accurate estimates of deforestation -Lack of receiving station for Central America and Central Africa (Landsat TM5)
Fallow C density	**22.4**	- Lack of data availability for fallow land - Likely to affect countries where fallow occupies a significant fraction of the territory

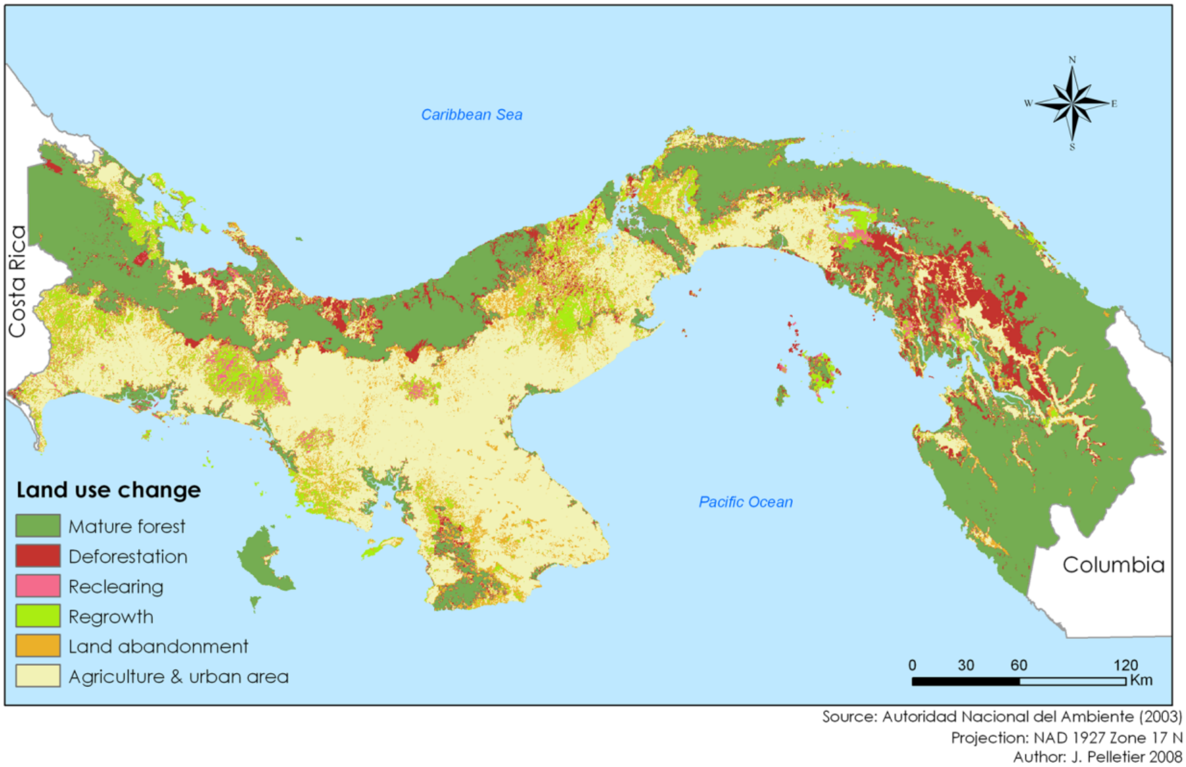

Figure 1. Land-cover change in Panama between 1992 and 2000. Much mature forest clearing occurred in Eastern Panama (Panama and Darién provinces). Secondary forest regrowth, plantations, and fallow land are mainly in Central Panama (Panama Canal watershed) and in Western Panama (Chiriqui, Bocas del Toro and Veraguas provinces and the Ngöbe-Buglé indigenous reserve). The reclearing of secondary forest took place mainly in Western Panama (Ngöbe-Buglé indigenous reserve).

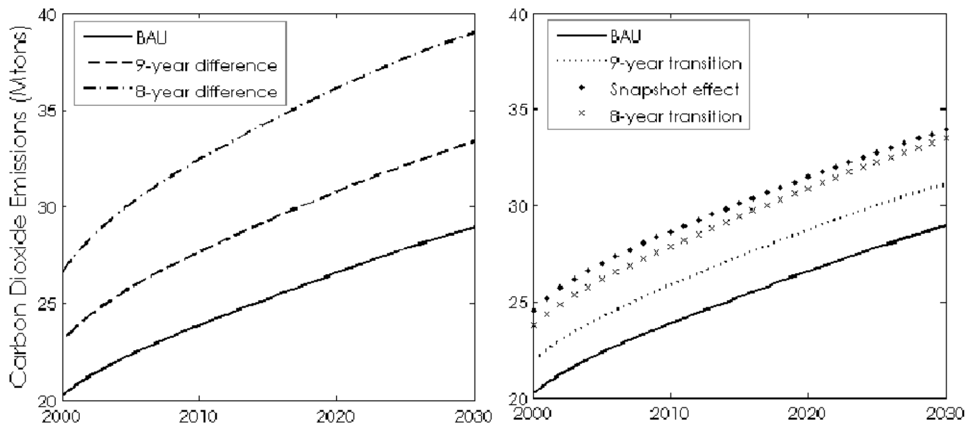

Figure 2. Sensitivity of emissions to errors in land-cover maps (uncertain timespan and snapshot effect). For the REL, ten years of difference between the two land-cover maps (1990 and 2000) is considered. The left pane shows the effect of assuming a nine-year interval between the two land-cover maps produces 15.6 % higher emissions, and an eight-year interval, 35.2 % higher than the REL. The right pane show the part of the error on emission estimates caused by land-cover transitions after deforestation without changing deforestation rates, which resulted in a mean difference of 8.2% and 16.5 %, when using a 9-year and an 8-year interval respectively between the two maps . The snapshot effect sensitivity test was used to account for a shortened agriculture/fallow cycle obtained an average emissions 19.3 % higher than the REL.

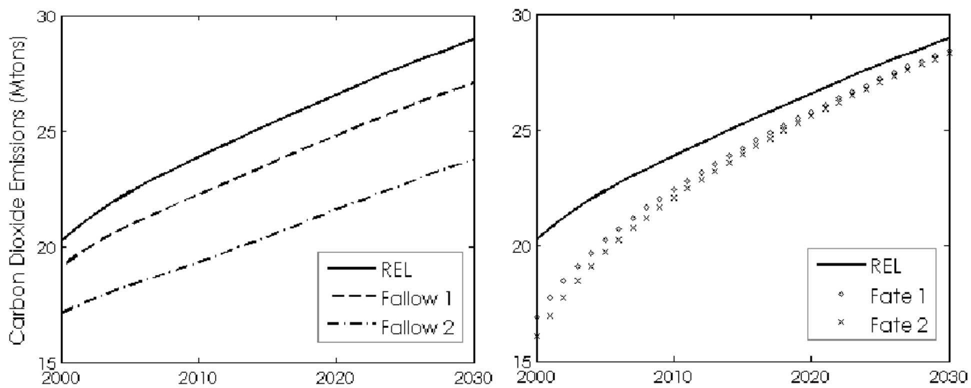

Figure 3. Results of the sensitivity analysis performed on the carbon value found in the fallow land-cover (left; REL= χ, Fallow 1= χ-10, Fallow 2= $\chi/2$) and on parameters linked to the fate of carbon after deforestation (right; REL (f_{burn} =0.6; f_{slash}= 0.339; f_{prod}= 0.061), Fate 1 (f_{burn} =0.4; f_{slash}= 0.4; f_{prod}= 0.2) , Fate 2 (f_{burn} =0.35; f_{slash}= 0.55; f_{prod}= 0.1)).

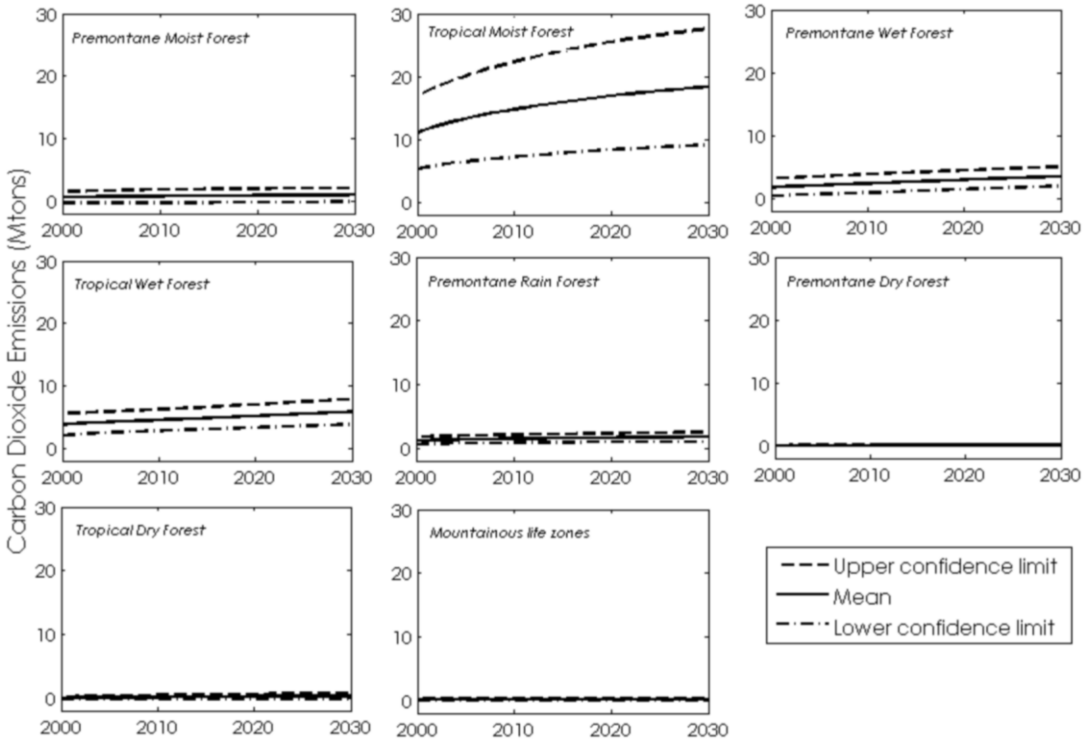

Figure 4. Mean emissions and confidence bounds (95% confidence intervals) of CO_2 emissions obtained from Monte Carlo simulation with 10,000 iterations to propagate the errors coming from input variables of the model per life zone. Moist Tropical forest, Premontane Wet forest and, Tropical Wet forest are the life zones with the greatest uncertainty.

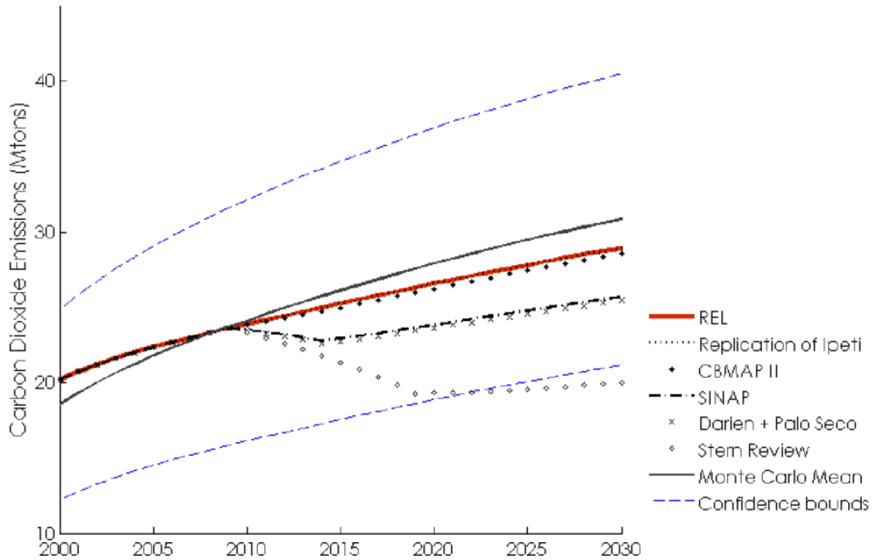

Figure 5. Comparison of the REL and five different scenarios to reduce emissions from deforestation in Panama with the confidence bounds (95% confidence intervals) and the mean obtained from the Monte Carlo uncertainty analysis. The red line represents the reference emission level, which is much closer to the upper confidence bound thus projecting higher emissions from land-cover change than the mean generated from the Monte Carlo simulation. Only the Stern Review scenario, with a reduction of deforestation of 50% would be detectable after 12 years of reduced deforestation when accounting for the overall uncertainty.

Linking statement 3

Amongst the error unveiled in the analysis of Chapter 2, the carbon flux associated with land-use dynamics following deforestation was largely ignored in the literature for the tropics. The lack of knowledge caused by the long time interval between two land cover assessments can cause us to overlook the dynamics associated with the agriculture-fallow cycle. From a carbon viewpoint, if fallow clearing for shifting cultivation is considered to be new deforestation the resulting estimates would overestimate emissions. Furthermore, fallow could be mistakenly identified as forest regrowth although it might be cut down again within a few years. I therefore contend that novel technical approaches are needed to adequately monitor shifting cultivation. Building on the results of Chapter 2, Chapter 3 focuses on the error associated with the so-called snapshot effect. Here, I proposed a new methodological approach showing that using a time series of satellite images to track forest clearance and regrowth, and thus provide insight on forest intervention over time, helps predict forest carbon stock change. Working in western Panama, in Palo Seco forest reserve, I coupled remote sensing analysis with a field-based forest carbon inventory to verify our approach. This chapter clears the path to other aspects of REDD+ related to biodiversity and community participation.

CHAPTER 3:

Traditional Shifting Agriculture: Tracking Forest Carbon Stock and Biodiversity through Time in Western Panama

Status: Pelletier, J., Codjia, C., Potvin, C. Traditional shifting agriculture: tracking forest carbon stock and biodiversity through time in western Panama. Global Change Biology, *In press*.

ABSTRACT

Reducing Emissions from Deforestation and forest Degradation (REDD+) requires developing countries to quantify green-house gas emissions and removals from forests in a manner that is robust, transparent, and as accurate as possible. While shifting cultivation is a dominant practice in several developing countries, there is still very limited information available on how to monitor this land-use practice for REDD+ as little is known about the areas of shifting cultivation or the net carbon balance. In the present work, we propose and test a methodology to monitor the effect of the shifting cultivation on above-ground carbon stocks. We combine multi-year remote sensing information, taken from a 12-year period, with an in-depth community forest carbon stock inventory in Palo Seco Forest Reserve, western Panama. With remote sensing, we were able to separate four forest classes expressing different forest-use intensity and time-since-intervention which demonstrate expected trends in above-ground carbon stocks. The addition of different interventions observed over time is shown to be a good predictor, with remote sensing variables explaining 64.2% of the variation in forest carbon stocks in cultivated landscapes. Multi-temporal and multi-spectral medium resolution satellite imagery is shown to be adequate for tracking land-use dynamics of the agriculture-fallow cycle. The results also indicate that, over time, shifting cultivation has a transitory effect on forest carbon stocks in the study area. This is due to the rapid recovery of forest carbon stocks, which results in limited net emissions. Finally, community participation yielded important additional benefits to measuring carbon stocks, including transparency and the valorization of local knowledge for biodiversity monitoring. Our study provides important inputs regarding shifting cultivation, which should be taken into consideration when national forest monitoring systems are created, given the context of REDD+ safeguards.

INTRODUCTION

As a new post-Kyoto climate regime is being negotiated under the United Nations Framework Convention on Climate Change (UNFCCC), countries have agreed to consider the Reduction of Emissions from Deforestation and Forest Degradation (REDD+), and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+) as relevant mitigation actions (UNFCCC 2010). Deforestation and forest degradation account for 12% to 17% of global greenhouse gas emissions (IPCC, 2007; van der Werf *et al.*, 2009). Developing countries that wish to participate in REDD+ have been requested to construct a reference emissions level/reference level, which is a benchmark for estimating emission reductions that are eventually achieved by REDD+. Participating nations are further requested to establish a national forest monitoring system to quantify emissions and removals from forests in a robust, transparent, and accurate manner.

In his analysis of global forest trends using the Food and Agriculture Organization's Forest Resource Assessment data set, Grainger (2008) has identified forest regrowth as an important source of uncertainty. Using the Republic of Panama as a model country, Pelletier *et al.* (2011) further showed that a poor understanding of land-use dynamics, which are related to the agriculture-fallow cycle or shifting cultivation, may induce up to 20% error in reference emission levels. An important fraction of Panama's territory oscillates between agriculture and fallow and, thus, the net carbon balance of this dynamic over time is not clear.

DeFries *et al.* (2007) have indicated that the land-use dynamics resulting from shifting cultivation or other temporary clearing may not produce net emissions over the long-term. Forest clearing for shifting cultivation releases less carbon than does permanent forest clearing because the fallow period allows some regrowth (Watson *et al.*, 2000). On average, carbon stocks would remain at some intermediate level associated with regrowth (Ramankutty *et al.*, 2007), depending on forest type and the length of fallow (Fearnside, 2000; Watson *et al.*, 2000). Successive interventions or repeated agriculture-fallow cycles, however, can affect species composition, reduce carbon storage capacity, and act as a precursor to the establishment of more permanent non-forest land cover (Peres *et al.*, 2006; Eaton & Lawrence, 2009).

According to IPCC (2003) temporary fallow should be considered as cultivated land, unless it corresponds to classification criteria defining forested land. In the humid tropics where trees grow rapidly, fallow land could effectively be classified as forest after just a few years. Therefore, under shifting cultivation, considering fallows as new deforestation could over-estimate related emissions (DeFries *et al*., 2007), while considering them as another type of croplands might underestimate emissions, since carbon density in fallow is higher than in most croplands (Tschakert *et al.*, 2007). To fully capture the dynamics of shifting agriculture, the management unit to be considered when monitoring emissions is the entire forest area rather than individual patches that have been cleared within the forest. Furthermore, we argue that shifting cultivation is akin to degradation rather than deforestation because of the temporary nature of fallow clearing. Of course, the consistency of the approach and the definitions that are used by countries to measure and monitor forests and the impacts of REDD+ activities, together with the importance of accounting for all significant fluxes, are at the root of good measurement and reporting practices.

In the context of REDD+, one common challenge to monitoring emissions that arise from shifting cultivation is the absence of clear guidance. Mertz (2009) showed that shifting cultivation systems are particularly difficult to capture because of the complex spectral signature of fields, fallows of various lengths, and the frequent inclusion of permanent farming. Multi-year assessments using a time series of satellite imagery have been suggested as an adequate means of tracking complex land-cover dynamics that include clearing and regrowth. Such assessments increase the possibility of detecting small-scale intervention (Stone & Lefebvre, 1998; Asner *et al.*, 2005; Broadbent *et al.*, 2006; Matricardi *et al.*, 2007), and by using sub-pixel information (Souza *et al.*, 2003; Brandt & Townsend, 2006; Matricardi *et al.*, 2010). Compelling research on selective logging has made use of methodologies that allow the extent of these activities to be quantified (Asner *et al.*, 2004b; Souza *et al.*, 2005a; Asner *et al.*, 2006). Forest carbon inventories, together with field information on land use practices and intervention histories, have been key to understanding the impacts that such activities have on forest carbon stocks (Gerwing, 2002; Asner *et al.*, 2004a; Souza *et al.*, 2005b) and, consequently, the estimation of selective logging contributions to CO_2 emissions.

In building on advancements made in studies of selective logging, our study provides a new approach to monitor degradation and forest carbon stock enhancement in the context of shifting cultivation which could be used under REDD+, by combining multi-year remote sensing information gathered over a 12-year period with an in-depth forest carbon stock inventory. Community participatory methods are used alongside remote sensing and forest carbon inventories to obtain comprehensive land-use history and information on the territory under study.

We focused on three aspects of forest intervention in western Panama: 1) forest area dynamics; 2) the ability to capture forest carbon density with the time series of vegetation indices and fraction images; and 3) the relationships between forest carbon density, land-use practices and biodiversity. Forest intervention, as it was considered in this research, reflected the multiple use of the study area by local inhabitants, who depend on natural resources for their livelihood, and was predominantly the result of shifting cultivation but also included the collection of firewood and timber for domestic use. We expected that the combined effects of interventions that were observed over time through remote sensing would enable us to predict forest carbon stocks in cultivated landscapes.

METHODS

Study Area

This study was conducted in the eastern part of the Palo Seco Forest Reserve (BPPS, *Bosque Protector de Palo Seco* in Spanish), which is a protected area covering 167,409 ha located on the Atlantic side of western Panama (Fig. 1) at the junction between the Talamanca Mountain Range and the Central Cordillera. Average daily temperature in the region is 26 ºC and the mean annual precipitation is > 2500 mm, which is evenly distributed throughout the year (ANAM/CBMAP, 2006).

According to ANAM/CBMAP (2006) about 10,000 people, mostly indigenous, presently live within the protected area; half of which overlaps with the indigenous territory *Comarca Ngäbe-Buglé*. Although the BPPS is a multi-use protected area where the collection of firewood and construction timber for domestic use is permitted, together with subsistence agriculture (J. Mosaquites, *personal communication*), the Comarca Ngäbe-Buglé itself experienced the highest annual rate of deforestation (-2.3%) in the country between 1990 and 2000 compared to the other provinces (ANAM/ITTO, 2003).

Previously described as pristine forest (Gaceta Oficial de Panamá, 28 de septiembre de 1983), the area where the field study was conducted was not colonized until 1975 by the Ngäbe, who had migrated from the Cricamola River Delta. At the time of our study, the population was 549 inhabitants. Multiple varieties of bananas, peach palms, and various tuber crops are cultivated within a shifting cultivation system, resulting in a mosaic of fallow plots of different ages. Because of the absence of a distinct dry season, the vegetation that is cleared in this system for new farms or from fallow land is usually not burned but is left to decay in the fields (Smith, 2005). According to household interviews in the area, the period of cultivation (mean + SD) was 1.7 ± 1.5 y, while that of fallowing was 3.8 ± 2.6 y. Fallow length vary considerably according to the crops that are planted. More than half of the respondents had at least 3.6 ha ± 5.4 ha of land in fallow for more than five years (Pelletier, 2012). Aggregate land use of 45 households that were interviewed consisted of 90 ha of crops, 163 ha of old fallow (> 5 y), and 195.5 ha of young fallow (< 5 y) (J. Pelletier, *unpublished data*). The use of fire has been limited to the creation of pasture for cattle ranching, which is not a dominant land-use practice, and has even declined in the area, according to local residents (Pelletier, 2012).

Remote Sensing Analysis

The surface area that was covered by the remote sensing analysis is 60 x 60 km. In-depth field information that was collected in this study concentrated on a specific area of over 1500 ha. The effect of forest intervention on forest carbon density was studied using a time-series of five satellite images taken between 1999 and 2011. The limited availability of cloud-free images determined the study to less than a 4-year temporal resolution and required the used of both ASTER and Landsat TM5 imagery. Figure 2 presents a schema of the remote sensing analysis.

Preprocessing of the images

The images were radiometrically, atmospherically, and geometrically corrected to facilitate detection of change over time. Each image was submitted to atmospheric and radiometric correction using REFLECT software that was based on 6S code routines (Bouroubi *et al.*, 2010). Orthorectification of each image was performed using ground control points (GCP) collected with a Garmin Legend HCx GPS device (Garmin International, USA; WAAS system-enabled) and, using the nearest neighbors re-sampling method, images were brought to a 15m pixel resolution (Table 1).

A supervised classification separated each image into five cover classes (cloud, shade, water, forest, agriculture) using maximum likelihood classification. Cloud and shade masks were used to create a forest/non-forest binary map and to mask out non-forest areas. Forest maps were created for the years 1999, 2000, 2004, 2007, and 2011. These procedures were performed in Geomatica (version 9.1, PCI Geomatics).

Image processing

Vegetation and Near-Infrared indices

We selected three Vegetation and Near-Infrared indices to be applied on each image. First, the Normalized Difference Vegetation Index (NDVI) calculated as:

$$NDVI = \rho_{NIR} - \rho_{red} / \rho_{NIR} + \rho_{red} , \quad (1)$$

where ρ_{NIR} is the reflectance at the near infrared band and ρ_{red} is the reflectance at the red band.

Second, the Modified Soil Adjusted Vegetation Index (MSAVI), an index bringing together the Soil Adjusted Vegetation Index (SAVI) and the Transformed Soil Adjusted Vegetation Index (TSAVI) (Huete, 1988; Qi *et al.*, 1994) where.

$$MSAVI= (1+L)(\rho_{NIR} - \rho_{red})/(\rho_{NIR} + \rho_{red} + L) , \quad (2)$$

and

$$L= 1-2\alpha * NDVI * (\rho_{NIR} - \alpha \rho_{red})$$

α is the slope of the soil line calculated from a regression of the surface reflectance at non-forested areas in the study site in the red, near-infrared space.

Finally, the Modified Soil Adjusted Vegetation Index aerosols free ($MSAVI_{af}$), an index that uses Near-Infrared (NIR) and shortwave (SWIR) bands that are less sensitive to atmospheric disturbance than the red band. $MSAVI_{af}$ provided satisfactory results when studying forest degradation in the Amazon basin in areas affected by haze and smoke (Matricardi *et al.*, 2010).

It was calculated as:

$$MSAVI_{af} = (1+L)\,(\rho_{NIR} - 0.5\rho_{SWIR})/(\,\rho_{NIR} + 0.5\rho_{SWIR} + L)$$

where ρ_{SWIR} is the reflectance of the Shortwave infrared band.

Endmember selection and spectral mixture analysis

The pixels composing a satellite image effectively display spectral combinations or mixtures of materials (e.g., 30% soil, 70% green vegetation). Pure pixels with reflectance spectra of a unique and well-characterized material can be used to separate the contributions of different materials to mixed pixels. These pure pixels represent landscape features that are spectrally distinct and which are referred to as end-members. They are used in spectral mixture analysis to linearly separate the fractions of each pixel that display the spectral characteristics of the reference end-members (Adams *et al.*, 1995; Souza Jr *et al.*, 2005). Spectral mixture analysis-based classification transforms the pixel reflectance that is obtained from all bands into fractions of reference end-members. Fraction images are more intuitive to interpret as they indicate the contributions of observable materials on the ground.

To select end-members, six image subsets (400 x 400 pixels) that represented a variety of land cover types were extracted from each image of the time series. A principal component analysis (PCA) was used to identify subsets' maximum scores. The pixels were visualized in multidimensional space in Matlab to examine their positions relative to the main axis. The spectral curves and the image context were examined for the candidate end-members.

For each image, the selected end-members were those for which the pixels demonstrated the best fit of the linear spectral mixture model. The fit of the model was determined by the degree to which a small proportion of the fraction values laid outside the range 0-1 and whether there was a small residual term in the mixture equation (Mather, 2004). The final model included three end-members: green vegetation, non-photosynthetic vegetation (e.g., wood debris), and soil.

Temporal change analysis

Each image was classified into Forest, Intervened forest, and Non-Forest[7] representing the intensity of forest-use practices in terms of canopy cover. Intervened forest was first classified as Forest in the binary map and then, identified using an index threshold on the MSAVIaf, green vegetation fraction, and soil fraction. The thresholds were chosen by comparing the index values of areas that were clearly identified as non-intervened forest and based on two years of field knowledge acquired by JP. In the context of REDD+, pixels classified as Intervened forest or temporarily as Non-Forest would be indicative of forest degradation. The 1999, 2000, 2004, and 2007 maps, which included the three classes (Forest, Intervened forest, Non-Forest) (Figure 3), were compared on a per-pixel basis to assess changes through time using map algebra in ArcGIS (ESRI, USA). The resulting forest cover change map revealed a complex land-cover dynamic, resulting in 81 classes. To adequately calibrate C stocks in the field, we simplified this forest cover change map according to the intensity of forest-use practices and time-since-intervention. The resulting map included four categories (Table 2): Forest, Old intervention (> 6 y), Deforested land that was revegetated, and Recent intervention (< 6 y). Pixels classified as Non-Forest throughout the time series were excluded from the field survey.

Forest Carbon Inventory

Hawth's Analysis Tools (version 3.27), which is an extension to ArcGIS, were used to generate stratified random sampling points for the four categories of the simplified forest cover change map (Figure 3). Forty-seven sampling points were chosen using a Garmin Legend HCx GPS device (Garmin International,USA). Each sampling point covered > 0.25 ha and a minimum of 11 sampling points were chosen per forest category for a total survey area of 13.3 ha. The area sampled for each category fell within the recommendations made to capture C stocks adequately in forested landscapes (Clark & Clark, 2000; Nascimento & Laurance, 2002; Chave *et al.*, 2004). Fieldwork took place in July-August 2010.

Seven men were selected by the local community to inventory forest carbon. The group, including individuals with a comprehensive knowledge of the local flora, was

[7] The term Non-forest in the image classification does not refer to permanent land-use change.

given three-day practical measurements training. After working for two weeks with JP, two teams were formed, one led by the local coordinator and the other by JP. The local coordinator obtained permission from landowners for the carbon inventory prior to field visits. A short survey of the landowners was conducted to determine land-use history and what products were extracted from the inventory plots.

Circular ground plots were deployed following Dalle & Potvin (2004). For each sampling location, four 15 m-radius plots were laid out on a 160-m transect for a total of 188 survey plots. This transect approach was chosen to account for forest heterogeneity. The geographic coordinates of each plot, together with its slope, were taken at its centre using a Vertex laser (Vertex IV Hypsometer/Transponder 360° Package; Haglöf Sweden).

The diameter at breast height (DBH, 1.3 m) of all trees, palms, lianas, herbaceous plants (banana tree), and tree ferns $\geq$ 10 cm DBH was measured to the nearest mm following rules detailed by Condit (1998) in each 15 m radius plot; a 6 m radius sub-plot was established for vegetation 5–10 cm DBH. The height of standing trees that had snapped below the crown was estimated. Downed woody debris $\geq$ 10 cm were measured following Kirby and Potvin (2007). Following IPCC (2003) guidelines, a key category analysis was performed on 20 plots representing the four forest categories. We established two 3 x 3 m quadrats to measure basal diameter (BD, 10 cm above ground level) of all saplings, shrubs, palms and lianas that were < 5 cm and $\geq$ 1 cm BD. Litter and all vegetation with BD < 1cm was harvested in a 50 x 50 cm quadrat (Kirby and Potvin 2007). As these pools were relatively unimportant, they were not measured in the other 168 plots. Below-ground C stocks and soil organic C (SOC) were not measured, in part because of complications involved in taking direct measurements. SOC dynamics in shifting cultivation systems are variable, with some studies finding that SOC contents are relatively unaffected by this practice (Tschakert *et al.*, 2007; Bruun *et al.*, 2009).

We identified 7056 individual plants $\geq$ to 5 cm DBH, which corresponded to 167 morphospecies. Local Spanish or Ngäberé names, leaves (flowers and fruits when available) of the most common trees species, photographs of leaves and trunks were collected to support identification. Leaf specimens were pressed, dried, and identified to genus or family by Professor Mireya D. Correa A., Director of the National Herbarium of Panama and botanist with the Smithsonian Tropical Research Institute (STRI).

Biomass calculation and carbon estimation

Allometric models were used to convert vegetation and woody debris measurements to above-ground biomass (AGB) (Table 3). We first estimated AGB at the plot level (Mg) and scaled the per hectare value by correcting plot size or transect length for the slope (Van Wagner, 1982). AGB was converted to C using a mean 47% C value for the biomass content of trees, palms, and lianas (Kirby & Potvin, 2007), and assuming the same percentage for fern and banana trees. A C fraction equivalent to 50% of the biomass content was used for coarse woody debris.

Statistical Analysis

We studied changes in forest carbon stock in relation to (i) the time series of vegetation indices and fractions, as well as (ii) land use and biodiversity.

A spatial correlogram based on Moran's I coefficient detected a slightly significant spatial correlation for forest carbon density in the field at the smallest distance class (< 200 m). We took the residuals to control for the transect effect of the forest carbon stock variable (n = 188) or we aggregated the data per transect (n = 47; 4 plots each) by using the mean C value.

For each image of the time series, we extracted the means of six remote sensing variables (including vegetation indices, and Green vegetation, Non-photosynthetic vegetation, and Soil Fractions) that corresponded to each field plot using the polygon zonal statistics available with Hawth's Analysis Tools. These remote sensing variables were used as explanatory variables that conveyed information about past interventions. Forest above-ground carbon stocks were used as the dependent variable.

To evaluate the classification of the four forest categories, we performed a linear discriminant analysis (LDA) on the remote sensing variables for the 188 plots that were visited. The indices were normalized using Box-Cox transformation prior to analysis; five outliers were identified as being contaminated by cloud or haze and were removed (Legendre & Legendre, 2012), leaving 183 observations for the LDA.

Two multiple regression models were used to predict total above-ground C (univariate response variable: sum of standing C + down woody debris C) with backward elimination of remote sensing variables from either 1999 to 2007 (n = 47) or 1999 to 2011 (n = 28; missing data due to cloud contamination of the 2011 image) data series.

The relation between biodiversity measures (biodiversity indices and identity of dominant morphospecies), land-use types, spatial structure as explanatory variables, and Standing C and down Woody debris C, as response variables, was examined by Redundancy Analysis (RDA). Three biodiversity indices, the richness (number of species per plot), the Shannon diversity number (exp(H), where $H = - \Sigma p_i \ln(p_i)$, and where p_i is the proportional abundance of species i, and Simpson diversity number (1/D, where $D = \Sigma(p_i)^2$), were included to the RDA model. Five spatial variables representing spatial structures at different scales and selected with the use of distance-based Moran's eigenvector maps (db MEM) (Borcard *et al.*, 2011) were also included in this RDA model. Prior to analysis, the numeric explanatory variables were normalized and standardized while the response variables were normalized. Global forward selection was used to obtain a parsimonious RDA model and verify for inflated variance (VIF), in order to minimize the correlation among variables (Borcard *et al.*, 2011). This procedure resulted in a simplified model consisting of the land-use types (categorical), the richness, the identity of the dominant (categorical) and one spatial variable (medium scale).

We used variation partitioning in order to quantify the various unique and combined fractions of the variation in above-ground C explained by each explanatory variable. Each explanatory dataset was forward selected separately in order to assess the magnitude of the various fractions, including the combined ones (Borcard *et al.*, 2011). The explanatory datasets included three biodiversity indices, identity of the dominant, land-use, and five spatial variables (db MEM). The categorical variables (land-use types and the Dominant identity) were recoded as dummy binary variables (Legendre & Legendre, 2012). Variation partitioning was performed with the varpart() function of the vegan package in R (Oksanen *et al.*, 2011).

One-way ANOVA and subsequent multiple means comparisons (post-hoc Tukey HSD) examined differences in forest carbon stocks among forest-use categories that were derived from the remote sensing analysis and in forest carbon stocks among land use types observed from the field and verified with the landowners. In both cases, we controlled for the transect effect. For the Forest category that was identified with remote sensing, five plots were excluded as they had been cultivated since the last image in 2007. Also, Pearson product-moment correlations (r) were calculated between the plant with the greatest DBH in the plots and total above-ground C. All statistical analysis was performed in R (R Development Core Team, 2005).

RESULTS

Tracking changes in forest areas

A major study objective is to develop a better understanding of changes in forest carbon stocks through time following human intervention. Our ability to fully understand changes in forest area over 1,500 ha during the time period covered by the satellite imagery (12 years) (Figure 5) was impeded by cloud cover in 2007 and 2011. Forest area diminished from 1999 to 2004, and part of the intervened forest area was reduced, with a corresponding increase in non-forested areas from the beginning of 1999 to the end of 2000 (Figure 5).

Spatially explicit tracking of Forest pixels shows that a large fraction of the Non-forest or Intervened forest pixels reverted to Forest through time, indicating a cyclical rather than linear pattern of land use change. This land-use dynamic among the Forest, Intervened forest, the Non-forest land is illustrated for 1999 to 2004 (Figure 3).

Discriminant Analysis (LDA) correctly classified 80.7% of the observations. Of the four forest-use categories, the “Forest” category was most efficiently classified on the basis of remote sensing variables (86.3% correct classification), while “Recent intervention” was least strongly differentiated from the other categories (75.8%) (Table 4). The bi-plot of the discriminant analysis shows the groups’ separation among the categories of Forest, Deforested revegetated and Interventions for the first two axes (Figure 6). The bi-plot of the second and third axes showed the separation between Old and Recent interventions (Data not shown).

ANOVA was used to compare forest carbon stocks of the four forest categories obtained from remote sensing. The respective mean total above-ground C stocks for the Forest, Old Intervention, Deforested Revegetated, and Recent Intervention groups were

99.1 ± 12.0 Mg ha^{-1}, 85.1 ± 10.6 Mg ha^{-1}, 65.0 ± 9.2 Mg ha^{-1}, and 52.2 ± 7.4 Mg ha^{-1}. Significant difference between categories was found ($F_{3, 179} = 5.19$, p=0.0019), specifically between Forest and Recent intervention categories (Tukey HDS; p = 0.006), as well as Forest and Deforested Revegetated (Tukey HDS; p = 0.030). Old intervention did not differ significantly from the other forest categories.

The Deforested revegetated category that was identified by remote sensing was consistent with the field information in 83% of cases (44 of 53 plots). Four sites that were mis-attributed, had experienced landslides in a section of the plot (3), or were adjacent to a landslide (1), while one other site was used to harvest fuel and construction wood (but not deforested) according to the field information. Wood harvesting may have been more intensive in this area at a particular point in the past, which could have resulted in the area exhibiting low above-ground C (50.7 Mg ha^{-1}). Only four plots visited remain inconsistent relative to the remote sensing analysis (8 %).

Explaining forest carbon density with the time series of remote sensing variables

Total above-ground C (Standing C + woody debris C) was regressed against the remote sensing variables. Cloud cover in 2011 that obscured sampling plots resulted in a lack of information for some transects. In this first analysis, remote sensing variables for 2011 were excluded for 47 transects (i.e., 188 plots). Multiple linear regression included seven remote sensing variables, which explained 64.2% of the variation in forest carbon density (R^2-adjusted = 0.578; Table 5). None of the remote sensing variables stood out as indubitably superior to the others. Substantial collinearity between some indices/fractions (NDVI, MSAVI, $MSAVI_{af}$) of the same year is evidence that some remote sensing variables from the same year could be interchanged with only small changes in explanatory power. Every year of the time series was represented in the multiple regression models, suggesting that the cumulative effect of intervention on forest explains carbon stock density better than simple examination of the results from any single year.

A second multiple regression, with reduced sampling size including 2011 (n=28) explained 47.1% (R^2-adjusted = 0.401) of the variation in standing above-ground C and woody debris C with a regression model based on the NPV Fraction 1999, Soil Fraction 2011 and MSAVIaf 2007.

Explaining forest carbon density with the land-use practices and biodiversity

The effect of land use and biodiversity on forest carbon stocks was explored using RDA, which demonstrated that 61.4 % of the variation in above-ground standing carbon stocks and woody C is predicted by the explanatory matrix including land use, dominant species identity, plot species richness, and space from db MEM (R^2-adjusted = 0.422).

The RDA ordination triplot shows that the explanatory variable most closely related to standing C is species richness, while the space had the highest loadings for woody debris (Figure 7). Not surprisingly, Crop and Fallow land-uses are negatively related to Standing C but slightly positively related to Woody debris C. The presence of *Sangrillo, Mayo,* or *Zapatero* trees as dominant species is associated with high levels of Standing C. Conversely, the *banano*, which is one of the main plants that is cultivated in croplands, is associated with low levels of Standing C, together with *Guarumo*, *Penca* and *Balso*, which are abundant in fallow lands.

Variance partitioning shows that dominant morphospecies identity alone explained 26.2% of Standing C plus woody debris (Figure 8). Together the land use variables and the biodiversity indices explained 7.1% of the variance. Land use has an effect on both biodiversity and the identity of the dominant species. The combination of these three variables explains 14.2% of the variation. Spatial components alone play a minor role in explaining variation (i.e., 2.4%). Last, the Pearson's correlation between the DBH of the dominant tree in each plot and total above-ground C is positive with r = 0.897, n=186, p < 2.2e-16.

ANOVA compared the carbon stocks of four land-use classes that were identified in the field. Mean total above-ground C (and associated standard errors) differ significantly among land-use classes ($F_{3,184}$ = 24.59, p <0.0001). Stocks were highest for Forest (112.5 ± 10.8 Mg C ha^{-1}), intermediate for Old fallow/Secondary forest and Fallow land (78.4 ± 12.2 Mg C ha^{-1}; 54.0 ± 6.0 Mg C ha^{-1}) and lowest for Cropland (29.1 ± 6.7 Mg C ha^{-1}; Figure 9). Forest above-ground C does not differ from Old Fallow/Secondary forest but does differ from that of Fallow and Croplands, which in turn differs significantly from Fallow and Old fallow/Secondary forest (Table 6).

DISCUSSION

The lack of knowledge of the land-use dynamics that are associated with the agriculture-fallow cycle has been shown to affect the accuracy of forest emission estimates (Pelletier et al., 2011). Our study provides 1) a new methodological approach to tracking the dynamics of shifting cultivation areas using affordable medium-resolution imagery and to help predict forest carbon stock changes, 2) evidence that shifting cultivation may have limited effects on forest C stocks over time, and 3) support for community monitoring to evaluate related forest carbon changes, with a variety of side benefits. The findings that are presented below are relevant to the monitoring of forest degradation and C stock enhancement for REDD+ in shifting cultivation areas.

Methodology for assessing impacts of shifting cultivation

Shifting cultivation landscapes are characterized by a mosaic of different land-use types that change through time (Mertz, 2009; Padoch & Pinedo-Vasquez, 2010). There is a general lack of knowledge regarding shifting cultivation and fallow area (Fearnside, 2000; Houghton, 2010), location and intensity of this practice (Hett *et al.*, 2011b). New ways to look at these shifting cultivation landscape mosaics have been proposed and could be very useful in spatially delineating these areas (Messerli *et al.*, 2009; Hett *et al.*, 2011b; Hett *et al.*, 2011a). In the context of REDD+, quantifying C emissions and removals from forests in these complex land-use systems is challenging and requires insights into their temporal dynamics. In effect, shifting cultivation may involve a change in carbon stocks without a change in forest area, making it more difficult to detect these activities through satellite imagery (Houghton, 2005). Here, we have shown that our approach using multi-temporal analysis of satellite images can effectively capture complex land-use dynamic of small-scale land-use processes that would not be traceable using only one point in time. Spatially explicit information on pixel transitions over time allows clearings that are temporary to be differentiated from those that remain deforested. We propose that, in the REDD+ context, those temporary clearings should be considered as degradation. We argue that, by monitoring these shifting cultivation areas adequately, we can avoid possible errors of inflating deforestation rates (DeFries et al., 2007) or of omitting the effect of fallow clearings.

In effect, the monitoring of shifting cultivation brings with it quite different technical problems than selective logging, because of its patchy spatial structure. When monitoring selective logging, visible patterns that are associated with log decks, roads, and skid marks facilitate its detectability (Stone & Lefebvre, 1998; Asner *et al.*, 2005; Laporte *et al.*, 2007). For small-scale shifting cultivation, interventions near villages and rivers or road networks are more likely to be identified but may still require ground verification. The type of crops that are planted and the use of fire in shifting cultivation systems may influence the detectability of planted plots; burned areas being more easily detected.

On the basis of the remote sensing analysis performed, we were able to discriminate between different intensities of forest-use and time-since-intervention, both of which have consequences on forest C stock with the following trend: Forest→Old intervention (>6yrs)→Deforested revegetated→Recent intervention (<6yrs). Forest and Recent intervention (<6yrs) as well as Forest and Deforested devegetated mean aboveground C presented a significant difference. These results are consistent with research that has been conducted in Amazonia, where more intense intervention categories (logged and burned forests) present significant differences from intact forest in terms of biomass (Souza *et al.*, 2005b). The mean C density of plots that were classified as Forest by remote sensing is 13.4 Mg C ha^{-1} lower than for the Forest class that was identified in the field survey (Figure 9). This difference may be the result of undetected forest use by remote sensing. It is possible, for example, that the Forest category might have been subject to intervention prior to our time series, i.e., prior to 1999, which would explain why it contains lower carbon stocks than intact forest. This limitation might be overcome with the use of longer time series.

Furthermore, the results of multiple regression indicate that the tracking of land-use dynamics over time can help quantify forest carbon stocks in a human-intervened landscape. In this shifting mosaic, we show that cumulating (multiple) interventions over time can be a good predictor of forest C stock changes. Effectively, in shifting cultivation areas, detecting intervention over time could act as an adequate indicator, which could be integrated into a forest monitoring system for tracking carbon stock changes.

In a GOFC-GOLD (2010) report, it was suggested that images that were separated by sufficiently long periods of time should be used for forest monitoring to avoid erroneous conclusions with respect to increases in forest areas. In contrast, we propose that understanding of a periodic process that is associated with shifting cultivation requires periodic analysis notions. Statistical theory states that the observational window for periodic events in a series must have a minimum length of two cycles, and its minimum frequency must be at least half a cycle (Legendre & Legendre, 2012). Clearings for shifting cultivation that are used for one year before abandonment and may be recultivated after 5 years (1 cycle = 6 years); therefore, the length of the time series should be 12 years with a frequency of observation at least every three years. In order to detect possible agricultural intensification that would be indicated by shortened fallow length, which would produce more C emissions, having adequate temporal resolution is important.

This research gives a positive result by providing a low-cost option for countries that are interested in monitoring shifting cultivation areas in terms of forest degradation and C stock enhancement for REDD+. In effect, only affordable and largely available medium-resolution images are required to perform this analysis.

Impacts of shifting cultivation on carbon stocks

One of the objectives of this study is to understand the role of shifting cultivation in terms of its impact on greenhouse gas emissions. The results obtained for the land use classes as identified in the field suggest a continuum indicative of forest regrowth with carbon stock replenishment, as observed by a C increase from Cultivation→Fallow→Old fallow/Secondary forest→Forest. Moreover, differences in mean above-ground C among classes diminish with time. It also signals that substantial above-ground C stocks can be held within fallow vegetation. These results are consistent with the idea that this shifting mosaic of temporary cleared areas would have limited long-term net emissions, as vegetation regrowth during the fallow period balances the emissions produced by vegetation clearing (DeFries et al., 2007). It is important to reiterate that cloud cover limited our ability to determine the net balance in forest areas; we do not know whether the deforested area is increasing or not.

The short time frame and capacity for forest to restore C stocks can be explained by the nature of the interventions in the landscape where we worked. The prevalence of agroforestry, the small scale of agricultural plots, the proximity to mature forest (seeds), short-lived interventions, and the forest-dominated landscape matrix are characteristics that may have contributed to rapid C stock recovery (Chazdon, 2003; Robiglio & Sinclair, 2011). The residual living vegetation, which affects the succession process (Turner et al., 1998), may explain why there is no difference between the Forest and Old fallow/Secondary forest classes in terms of carbon stock density, the latter having a larger within-group variance. Also, if big trees are left untouched, as it has been observed on old pasture in the study area, the intervention effect on C stock may be limited (Laurance *et al.*, 2000; Feldpausch *et al.*, 2005).

The rapid recovery of forest carbon stocks following shifting cultivation supports the view that forest and land uses can maintain important ecosystem services, while they also fulfill a fundamental activity in the economy of local communities as a multi-use system (Noble & Dirzo, 1997). Shifting cultivation has been singled-out as an environmentally destructive and primitive practice and perceived until recently as one of the main drivers of deforestation in the tropics (Geist & Lambin, 2001; Mertz, 2009; Padoch & Pinedo-Vasquez, 2010). This perception is being challenged by numerous studies, which show that shifting cultivation in many situations can be a rational economic and environmental choice for poor farmers in the tropics (Toledo *et al.*, 2003; Ickowitz, 2006; Nielsen *et al.*, 2006; Harvey *et al.*, 2008). Our results support the view that shifting cultivation can have a transitory impact on forest carbon stocks and may contribute to the maintenance of ecosystem services, such as carbon reservoirs in human-modified landscapes (Ickowitz, 2006; Fischer *et al.*, 2008; Harvey *et al.*, 2008; DeClerck *et al.*, 2010; Padoch & Pinedo-Vasquez, 2010). Of course, the intensification of land-use practices, including shortening of the fallow period, may change these conditions (Eaton & Lawrence, 2009; Dalle *et al.*, 2011; Robiglio & Sinclair, 2011).

While land use has a direct effect on forest C stocks, the identity of the dominant species on C alone stands out as the most important factor in explaining variation in above-ground C stocks. On one hand, this information is consistent with other observations (Kirby & Potvin, 2007; Ruiz-Jaen & Potvin, 2010) and perhaps, could be explored further for its use as a proxy measure of forest C stocks. On the other hand, land use practices that negatively affect dominant tree species (including *Zapatero*, *Sangrillo* and *Mayo,* which are timber species) may reduce carbon storage in the ecosystem (Kirby & Potvin, 2007). However, the landscape configurations that connect forest patches, maintain a diverse array of habitats, and retain high structural and floristic complexity as found in our study area, may help maintain biodiversity (Harvey *et al.*, 2008; Chazdon *et al.*, 2009).

These findings cannot necessarily be generalized to the overall protected area or to other area where different land-use practices may prevail. Shifting cultivation, as performed by Ngäbe people, is part of a social-ecological system that will differ substantially if compared to Latino colonists slash-and-burn practices. Also, C recovery from shifting cultivation in another forest type, such as the tropical dry forest for instance, would be expected to be slower (Brown & Lugo, 1990).

The value of community monitoring

Annex I of the Cancun Agreement adopted some of the guidelines and safeguards that should surround REDD+ activities (UNFCCC, 2010). These safeguards indicate that the full and effective participation of relevant stakeholders, in particular, indigenous peoples and local communities, should be promoted and supported when undertaking REDD+, including for monitoring activities. Skutsch *et al.* (2009) signals that, while several studies have looked at the capacity of local people to assess forest biodiversity or disturbance, only a few projects have trained local people to make detailed measurements of carbon stocks. Yet, community measurements can be a winning approach for assessments of carbon stocks and biodiversity, fulfilling important biodiversity monitoring which is well-aligned with the safeguards (CIGA-REDD, 2011). Our study provides further evidence to support not only the feasibility, but also the advantage of this approach. Working with local people has been particularly efficient for locating the randomly selected sampling points because of their knowledge of the territory. The workers, most of whom had primary education, were quick to learn the techniques and how to use the tools after capacity-building and field practice as observed by Skutsch (2005) and also probably resulted in more cost-effective study than if it had been done by professional foresters. In effect, Danielsen et al.(2011) conclude that, when examining the reliability and comparing the cost of community monitoring with forester-led measurements, local people can collect forest condition data of quality comparable to those collected by trained scientists, at half the cost.

Working with local people has brought more added-value than the strict measurement of carbon stocks alone. An additional advantage is incurred when the measurement of local biodiversity is facilitated through the application of traditional knowledge. Moreover, the complementary information provided by local experts and landowners on land-use history and practices is of great value in explaining carbon stock variation in the landscape. Finally, community member participation in carbon stock measurement contributed to the transparency of the process, which would have certainly generated much distrust if it had been done by outsiders.

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REFERENCES

Adams, J.B., Sabol, D.E., Kapos, V., Almeida Filho, R., Roberts, D.A., Smith, M.O. & Gillespie, A.R. (1995) Classification of multispectral images based on fractions of endmembers: Application to land-cover change in the Brazilian Amazon. Remote Sensing of Environment, 52, 137-154.

ANAM/CBMAP (2006) Plan de Manejo Actualizado: Bosque Protector de Palo Seco. Autoridad Nacional del Ambiente y Corredor Biologico Mesoamericano del Atlantico Panameno, Panama, Republica de Panama. 150 pp.

ANAM/ITTO (2003) Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. Autoridad Nacional del Ambiente, Panama, Republica de Panama. 107 pp.

Asner, G.P., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Knapp, D.E. & Silva, J.N.M. (2006) Condition and fate of logged forests in the Brazilian Amazon. Proceedings of the National Academy of Sciences USA, 103, 12947-12950.

Asner, G.P., Keller, M., Pereira, R., Zweede, J.C. & Silva, J.N.M. (2004a) Canopy damage and recovery after selective logging in Amazonia: Field and satellite studies. Ecological Applications, 14, S280-S298.

Asner, G.P., Keller, M. & Silva, J.N.M. (2004b) Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Global Change Biology, 10, 765-783.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M. & Silva, J.N. (2005) Selective logging in the Brazilian Amazon. Science, 310, 480-482.

Borcard, D., Gillet, F. & Legendre, P. (2011) Numerical Ecology with R. Springer.

Bouroubi, Y., Cavayas, F. & Tremblay, N. (2010) Les corrections radiométriques des images multispectrales et leur importance pour la fiabilité des applications de la télédétection, Sarrebruck, Germany.

Brandt, J.S. & Townsend, P.A. (2006) Land use-land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecology, 21, 607-623.

Broadbent, E.N., Zarin, D.J., Asner, G.P., Pena-Claros, M., Cooper, A. & Littell, R. (2006) Recovery of forest structure and spectral properties after selective logging in lowland Bolivia. Ecological Applications, 16, 1148-1163.

Brown, S. & Lugo, A.E. (1990) Tropical secondary forests. Journal of Tropical Ecology, 6, 1-32.

Bruun, T.B., de Neergaard, A., Lawrence, D. & Ziegler, A.D. (2009) Environmental consequences of the demise of swidden cultivation in Southeast Asia: Carbon storage and soil quality. Human Ecology 37, 375-388.

Chave, J., Condit, R., Aguilar, S., Hernandez, A., Lao, S. & Perez, R. (2004) Error propagation and scaling for tropical forest biomass estimates. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, 359, 409-420.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B. & Yamakura, T. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145, 87-99.

Chazdon, R.L. (2003) Tropical forest recovery: legacies of human impact and natural disturbances. Perspectives in Plant Ecology Evolution and Systematics, 6, 51-71.

Chazdon, R.L., Peres, C.A., Dent, D., Sheil, D., Lugo, A.E., Lamb, D., Stork, N.E. & Miller, S.E. (2009) The potential for species conservation in tropical secondary forests. Conservation Biology, 23, 1406-1417.

CIGA-REDD (2011) Report on the FCPF Workshop ¨Linking community monitoring with national MRV for REDD+.¨ CIGA-REDD, UNAM, Mexico City, 12-14 September 2011. 19 pp.

Clark, D.B. & Clark, D.A. (2000) Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management, 137, 185-198.

Condit, R. (1998) Tropical Forest Census Plots. Springer-Verlag, Berlin.

Dalle, S.P. & Potvin, C. (2004) Conservation of useful plants: An evaluation of local priorities from two indigenous communities in eastern Panama. Economic Botany, 58, 38-57.

Dalle, S.P., Pulido, M.T. & de Blois, S. (2011) Balancing shifting cultivation and forest conservation: lessons from a "sustainable landscape" in southeastern Mexico. Ecological Applications, 21, 1557-1572.

Danielsen, F., Skutsch, M., Burgess, N.D., Jensen, P.M., Andrianandrasana, H., Karky, B., Lewis, R., Lovett, J.C., Massao, J., Ngaga, Y., Phartiyal, P., Poulsen, M.K., Singh, S.P., Solis, S., Sorensen, M., Tewari, A., Young, R. & Zahabu, E. (2011) At the heart of REDD+: a role for local people in monitoring forests? Conservation Letters, 4, 158-167.

DeClerck, F.A.J., Chazdon, R., Holl, K.D., Milder, J.C., Finegan, B., Martinez-Salinas, A., Imbach, P., Canet, L. & Ramos, Z. (2010) Biodiversity conservation in human-modified landscapes of Mesoamerica: Past, present and future. Biological Conservation, 143, 2301-2313.

DeFries, R., Achard, F., Brown, S., Herold, M., Murdiyarso, D., Schlamadinger, B. & de Souza, C. (2007) Earth observations for estimating greenhouse gas emissions from deforestation in developing countries. Environmental Science & Policy, 10, 385-394.

Delaney, M., Brown, S., Lugo, A.E., Torres-Lezama, A. & Quintero, N.B. (1998) The quantity and turnover of dead wood in permanent forest plots in six life zones of Venezuela. Biotropica, 30, 2-11.

DeWalt, S.J. & Chave, J. (2004) Structure and biomass of four lowland Neotropical forests. Biotropica, 36, 7-19.

Eaton, J.M. & Lawrence, D. (2009) Loss of carbon sequestration potential after several decades of shifting cultivation in the Southern Yucatan. Forest Ecology and Management, 258, 949-958.

Fearnside, P.M. (2000) Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change, 46, 115-158.

Feldpausch, T.R., Jirka, S., Passos, C.A.M., Jasper, F. & Riha, S.J. (2005) When big trees fall: Damage and carbon export by reduced impact logging in southern Amazonia. Forest Ecology and Management, 219, 199-215.

Fischer, J., Brosi, B., Daily, G.C., Ehrlich, P.R., Goldman, R., Goldstein, J., Lindenmayer, D.B., Manning, A.D., Mooney, H.A., Pejchar, L., Ranganathan, J. & Tallis, H. (2008) Should agricultural policies encourage land sparing or wildlife-friendly farming? Frontiers in Ecology and the Environment, 6, 382-387.

Gaceta Oficial (28 de septiembre de 1983) Decreto Ejecutivo N° 25 "Por el cual se declara y se describe el Bosque Protector de Palo Seco en los Distritos de Chiriquí Grande y Changuinola, Provincia de Bocas del Toro". República de Panamá.

Geist, H.J. & Lambin, E. (2001) What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. LUCC Report Series 4. International Human Dimensions Programme on Global Environmental Change (IHDP) International Geosphere-Biosphere Programme (IGBP), Louvain-la-Neuve, Belgium. 136 pp.

Gerwing, J.J. (2002) Degradation of forests through logging and fire in the eastern Brazilian Amazon. Forest Ecology and Management, 157, 131-141.

GOFC-GOLD (2010) A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. GOFC-GOLD Report version COP16-1. GOFC-GOLD Project Office, Natural Resources Canada, Edmonton Alberta, Canada.

Grainger, A. (2008) Difficulties in tracking the long-term global trend in tropical forest area. Proceedings of the National Academy of Sciences USA, 105, 818-823.

Harvey, C.A., Komar, O., Chazdon, R., Ferguson, B.G., Finegan, B., Griffith, D.M., Martinez-Ramos, M., Morales, H., Nigh, R., Soto-Pinto, L., Van Breugel, M. & Wishnie, M. (2008) Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot. Conservation Biology, 22, 8-15.

Hett, C., Heinimann, A. & Messerli, P. (2011a) Spatial Assessment of carbon stocks of living vegetation at the national level in Lao PDR. Geografisk Tidsskrift, 111, 11-26.

Hett, C., Castella, J.C., Heinimann, A., Messerli, P. & Pfund, J.L. (2011b) A landscape mosaics approach for characterizing swidden systems from a REDD+ perspective. Applied Geography, 32, 608-618.

Houghton, R.A. (2005) Aboveground forest biomass and the global carbon balance. Global Change Biology, 11, 945-958.

Houghton, R.A. (2010) How well do we know the flux of CO2 from land-use change? Tellus Series B Chemical and Physical Meteorology, 62, 337-351.

Huete, A.R. (1988) A soil-adjust vegetation index (SAVI). Remote Sensing of Environment, 25, 295−309.

Ickowitz, A. (2006) Shifting cultivation and deforestation in tropical Africa: Critical reflections. Development and Change, 37, 599-626.

IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies (IGES), Japan.

IPCC (2007) IPCC Fourth Assessment Report: Climate Change 2007. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kirby, K.R. & Potvin, C. (2007) Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. Forest Ecology and Management, 246, 208-221.

Laporte, N.T., Stabach, J.A., Grosch, R., Lin, T.S. & Goetz, S.J. (2007) Expansion of industrial logging in Central Africa. Science, 316, 1451-1451.

Laurance, W.F., Delamonica, P., Laurance, S.G., Vasconcelos, H.L. & Lovejoy, T.E. (2000) Conservation - Rainforest fragmentation kills big trees. Nature, 404, 836-836.

Legendre, P. & Legendre, L. (2012) Numerical ecology, 3rd English ed. Elsevier Science BV, Amsterdam.

Mather, P.M. (2004) Computer Processing of Remotely-Sensed Images: an introduction, 3rd ed. John Wiley & Sons Ltd, Chichester, UK.

Matricardi, E.A.T., Skole, D.L., Cochrane, M.A., Pedlowski, M. & Chomentowski, W. (2007) Multi-temporal assessment of selective logging in the Brazilian Amazon using Landsat data. International Journal of Remote Sensing, 28, 63-82.

Matricardi, E.A.T., Skole, D.L., Pedlowski, M.A., Chomentowski, W. & Fernandes, L.C. (2010) Assessment of tropical forest degradation by selective logging and fire using Landsat imagery. Remote Sensing of Environment, 114, 1117-1129.

Mertz, O. (2009) Trends in shifting cultivation and the REDD mechanism. Current Opinion in Environmental Sustainability, 1, 156-160.

Messerli, P., Heinimann, A. & Epprecht, M. (2009) Finding homogeneity in heterogeneity - a new approach to quantifying landscape mosaics developed for the Lao PDR. Human Ecology, 37, 291-304.

Mosaquites, J. Personal communication. Administrator of the Bosque Protector de Palo Seco. Administración Regional de Bocas del Toro, Autoridad Nacional del Ambiente.

Nascimento, H.E.M. & Laurance, W.F. (2002) Total aboveground biomass in central Amazonian rainforests: a landscape-scale study. Forest Ecology and Management, 168, 311-321.

Nielsen, U., Mertz, O. & Noweg, G.T. (2006) The rationality of shifting cultivation systems: labor productivity revisited. Human Ecology, 34, 210-218.

Noble, I.R. & Dirzo, R. (1997) Forests as human-dominated ecosystems. Science, 277, 522-525.

Oksanen, J., F. , Blanchet, G., Kindt, R., Legendre, P., O'Hara, R.B., Simpson, G.L., Solymos, P.M., Stevens, H.H. & Wagnerm, H. (2011) vegan: Community Ecology Package. R package version 1.17-9. http://CRAN.R-project.org/package=vegan.

Padoch, C. & Pinedo-Vasquez, M. (2010) Saving slash-and-burn to save biodiversity. Biotropica, 42, 550-552.

Pelletier, J. (2012) Emissions from land-cover change in Panama: uncertainty, dynamics, and perceptions. Doctoral Thesis, McGill University, Montreal, QC. 232 pp.

Pelletier, J., Ramankutty, N. & Potvin, C. (2011) Diagnosing the uncertainty and detectability of emission reductions for REDD+ under current capabilities: an example for Panama. Environmental Research Letters, 6, 024005.

Peres, C.A., Barlow, J. & Laurance, W.F. (2006) Detecting anthropogenic disturbance in tropical forests. Trends in Ecology & Evolution, 21, 227-229.

Qi, J., Chehbouni, A., Huete, A.R., Kerr, Y.H. & Sorooshian, S. (1994) A modified soil adjusted vegetation index. Remote Sensing of Environment, 48, 119-126.

R Development Core Team (2005) R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A. & Houghton, R.A. (2007) Challenges to estimating carbon emissions from deforestation. Global Change Biology, 13, 51-66.

Robiglio, V. & Sinclair, F. (2011) Maintaining the conservation value of shifting cultivation landscapes requires spatially explicit interventions. Environmental Management, 48, 289-306.

Ruiz-Jaen, M.C. & Potvin, C. (2010) Tree diversity explains variation in ecosystem function in a Neotropical forest in Panama. Biotropica, 42, 638-646.

Skutsch, M., Van Laake, P., Zahabu, E., Karky, B. & Phartiyal, P. (2009) Community monitoring in REDD+. Realising REDD+: National strategy and policy options (ed. by A. Angelsen), pp. 101-112, Bogor, Indonesia.

Skutsch, M.M. (2005) Reducing carbon transaction costs in community based forest management. Climate Policy, 5, 433-443.

Smith, D.A. (2005) Garden game: Shifting cultivation, indigenous hunting and wildlife ecology in western Panama. Human Ecology, 33, 505-537.

Souza Jr., C.M., Roberts, D.A. & Cochrane, M.A. (2005a) Combining spectral and spatial information to map canopy damage from selective logging and forest fires. Remote Sensing of Environment, 98, 329-343.

Souza Jr., C.M., Roberts, D.A. & Monteiro, A. (2005b) Multi-temporal analysis of degraded forests in the southern Brazilian Amazon. Earth Interactions, 9, 1-25.

Souza Jr., C.M., Firestone, L., Silva, L.M. & Roberts, D. (2003) Mapping forest degradation in the Eastern Amazon from SPOT 4 through spectral mixture models. Remote Sensing of Environment, 87, 494-506.

Stanley, W., Brown, S., Kant, Z., Calmon, M., Tiepolo, G. & Boucher, T. (2010) The Climate Action Project Research Initiative. The Nature Conservancy, Arlington, VA.

Stone, T.A. & Lefebvre, P. (1998) Using multi-temporal satellite data to evaluate selective logging in Para, Brazil. International Journal of Remote Sensing, 19, 2517-2526.

Toledo, V.M., Ortiz-Espejel, B., Cortés, L., Moguel, P. & Ordoñez, M.D.J. (2003) The multiple use of tropical forests by indigenous peoples in Mexico: a case of adaptive management. Conservation Ecology, 7, 9 pp. URL: http://www.consecol.org/vol7/iss3/art9/.

Tschakert, P., Coomes, O.T. & Potvin, C. (2007) Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama. Ecological Economics, 60, 807-820.

UNFCCC (2010) Outcome of the work of the Ad Hoc Working Group on long-term Cooperative Action under the Convention. In: Draft decision [-/CP.16]. United Nations Framework Convention on Climate Change.

van der Werf, G.R., Morton, D.C., DeFries, R.S., Olivier, J.S.J., Kasibhatla, P.S., Jackson, R.B., Collatz, G.J. & Randerson, J.T. (2009) CO2 emissions from forest loss. Nature Geoscience, 2, 737-738.

van Noordwijk, M., Rahayu, S., Hairiah, K., Wulan, Y.C., Farida, C. & Verbist, B. (2003) Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. Science in China, Series C-Life Sciences 45, 75-86

Van Wagner, C.E. (1982) Practical aspects of the line intersect method. Petawawa National Forestry Institute Information Report PI-X-12. Canadian Forestry Service, Chalk River, Ontario. 11 pp.

Waddell, K.L. (2002) Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators, 1, 139-153.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. & Dokken, D.J. (eds.) (2000) Land Use, Land-Use Change and Forestry. Cambridge University Press, Cambridge, UK.

TABLES AND FIGURES

Table 1. Time series of satellite images

Satellite and sensor	Date of acquisition	Cloud Cover	Bands used	Ortho rms	Grid cell size	Number of GCPs
Landsat 5 TM	18/01/1999	0%	1-5,7	0.26	30 m	19
Landsat 5 TM	22/12/2000	0%	1-5,7	0.28	30 m	19
TERRA ASTER	02/02/2004	3%	VNIR[a]	0.56	15 m	19
			SWIR[b]	0.28	30 m	19
TERRA ASTER	14/03/2007	11%	VNIR	0.56	15 m	20
			SWIR	0.28	30 m	20
Landsat 5 TM[c]	03/01/2011	35%	1-5,7	0.23	30 m	17

[a] VNIR (Visible Near Infrared)

[b] SWIR (Short Wave Infrared)

[c] For the last image of the time series (2011), we ordered imagery to be collected while the fieldwork was performed. However, we had to wait for over six months to obtain a useable image as the rest were covered with clouds. Still, the Landsat image for 2011 is contaminated with clouds, resulting in missing data.

Table 2. Simplified forest cover change categories

	Description
Forest	Forests that have not undergone any observable forest intervention process over the period of the time series.
Older intervention (> 6 y)	Forest intervention (not classified as Non-Forest) observed on the 1999 and/or 2000 satellite images and classified as Forest in 2004 and 2007
Recent intervention (< 6 y)	Forest intervention (not classified as Non-Forest) observed on the 2004 and/or 2007 satellite image but that were classified as forest in 1999 and 2000
Deforested[b] revegetated	Forest-land that has been classified as Non-Forest on the 1999 and/or 2000 and/or 2004 images and classified as Forest in 2007[a].
Non-forest	Land that appeared deforested in 2007 and potentially during earlier years. Excluded from the sampling.
Cloud/Shade	Cloud/shade cover during 2007, the time period before the forest inventory, Excluded from the forest carbon inventory.

[a] For the purpose of the field survey performed in 2010, we decided that to avoid the risk of arriving in Non-Forest areas by not visiting plots classified as Non-Forest in 2007, as the focus of this survey was on forested areas.

[b] In order to be consistent with IPCC terminology, this category should be described as forest land remaining as forest land but temporarily unstocked. However, for simplification purposes, we called this category Deforested revegetated as we found it more descriptive of the activity taking place.

Table 3. Allometric models used to convert measures of vegetation and woody debris to AGB

	Source	Models	Units
Trees and palms >= 5cm DBH	Chave et al. (2005)	AGB= Exp[-1.239+1.98*Log(DBH)+0.207*(Log(DBH))^2-0.0281*(Log(DBH))^3]*ρi	Kg
Tree snags >=5 cm DBH	Nascimento and Laurance (2002)	AGB= ρi[BA*(Height)*0.78]	Mg
Dead trees >=5 cm DBH	Delaney et al. (1998)	90% of total AGB of live trees	Kg
Lianas >= 5cm DBH	DeWalt and Chave (2004)	AGB= Exp[0.298+1.027Ln(BA)]	Mg
Banana trees >=5cm DBH	van Noordwijk et al.(2003)	W=0.030DBH^2.13	Mg
Tree ferns >= 5cm DBH	Standley et al. (2010)	1135.3DBH-4814.5	g
Saplings < 5 cm DBH, >=1cm BD	Kirby and Potvin (2007)	Exp[3.965 + 2.383 ln(BD)]	g
Coarse Woody Debris	Van Wagner (1982); Waddell (2002)	[(π^2/8L)Σ(d^2)]ρdrc*Cs	Kg

AGB: Above Ground Biomass

DBH: Diameter at Breast Height (diameter at 1.3m above ground level; cm)

BD: Basal Diameter (diameter at 10 cm above ground level; cm)

BA: Basal Area (m2) or equation BA = pi(DBH)^2/40000

ρi = species specific wood density value (g cm -3) of tree (i), or 0.54 when wood density of species or species unknown

Cs: Slope correction factor sqrt(1+(%of slope/100)^2) or rprime=r/(cos(alpha))^2

ρdrc: Decay Class Reduction Factor; depending if sound ρdrc=0.453 g cm-3) or rotten ρdrc=0.319 g cm-3 (Clark et al., 2002); corrected for slope, not corrected for tilt of individual pieces

Table 4. Classification table obtained from the linear discriminant analysis classification function

	Objects assigned by the Classification function				Total correct in %
Forest Classification	Deforested Revegetated	Forest	Old Intervention	Recent Intervention	
Deforested Revegetated	42	6	4	1	**79.2**
Forest	7	56	2	0	**86.2**
Old Intervention	4	2	24	1	**77.4**
Recent Intervention	2	2	4	25	**75.8**
Total	53	65	31	33	**80.7**

Table 5. Parsimonious multiple regression model of total aboveground carbon stocks in relation to vegetation indices/fractional components after backward elimination and reduction of collinearity (n = 47).

Variables	**Coefficient**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	1.36E-14	2.32E-01	0	1
NDVI_2000	2.40E+00	5.09E-01	4.726	2.96E-05
MSAVIaf_2000	-1.82E+00	5.54E-01	-3.286	0.002157
FracGV_2007	-1.13E+00	3.13E-01	-3.601	0.000883
FracNPV_1999	-1.34E+00	2.92E-01	-4.61	4.25E-05
NDVI_2004	1.61E+00	4.24E-01	3.788	0.000513
FracSoil_1999	1.41E+00	3.86E-01	3.659	0.000748
FracSoil_2004	1.45E+00	3.92E-01	3.697	0.000669

Residual standard error: 1.592 on 39 degrees of freedom
Multiple R-square: 0.6421,   Adjusted R-square: 0.5779
F-statistic: 9.995, on 7 and 39 DF, p-value: 4.399e-07

Table 6. Post-hoc multiple comparison tests with Tukey HSD. Significant differences are identified in bold.

Land-use classes	diff	lwr	upr	p adj
Old fallow/Secondary forest-Forest	-0.28771	-0.6507	0.075287	0.172004
Crop-Forest	**-0.98456**	**-1.31776**	**-0.65136**	**0**
Fallow-Forest	**-0.58079**	**-0.82184**	**-0.33975**	**0**
Crop-Old fallow/Secondary forest	**-0.69685**	**-1.12896**	**-0.26475**	**0.00026**
Fallow- Old fallow/Secondary forest	-0.29309	-0.65887	0.072698	0.164379
Fallow-Crop	**0.403766**	**0.067535**	**0.739997**	**0.011428**

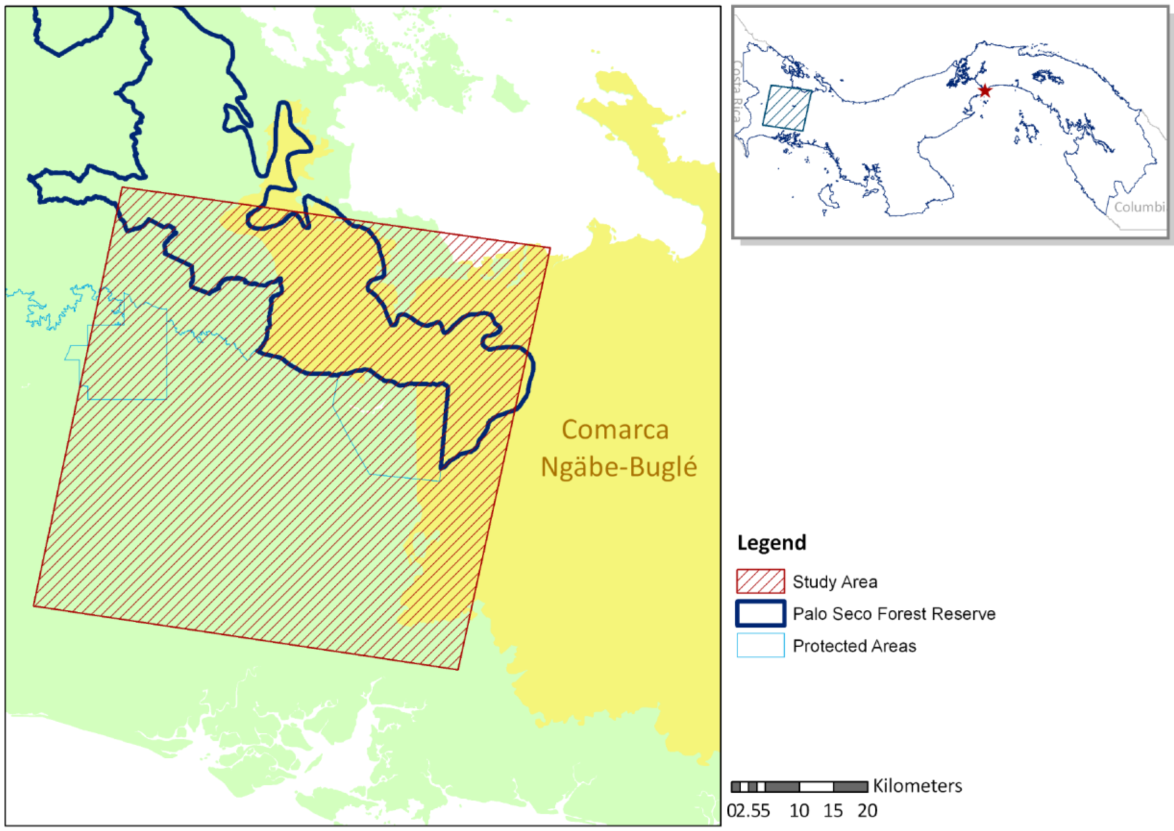

Figure 1. Regional map presenting the area covered by the remote sensing analysis. Note that part of the Palo Seco Forest Reserve falls with the Ngäbe-Buglé indigenous territory.

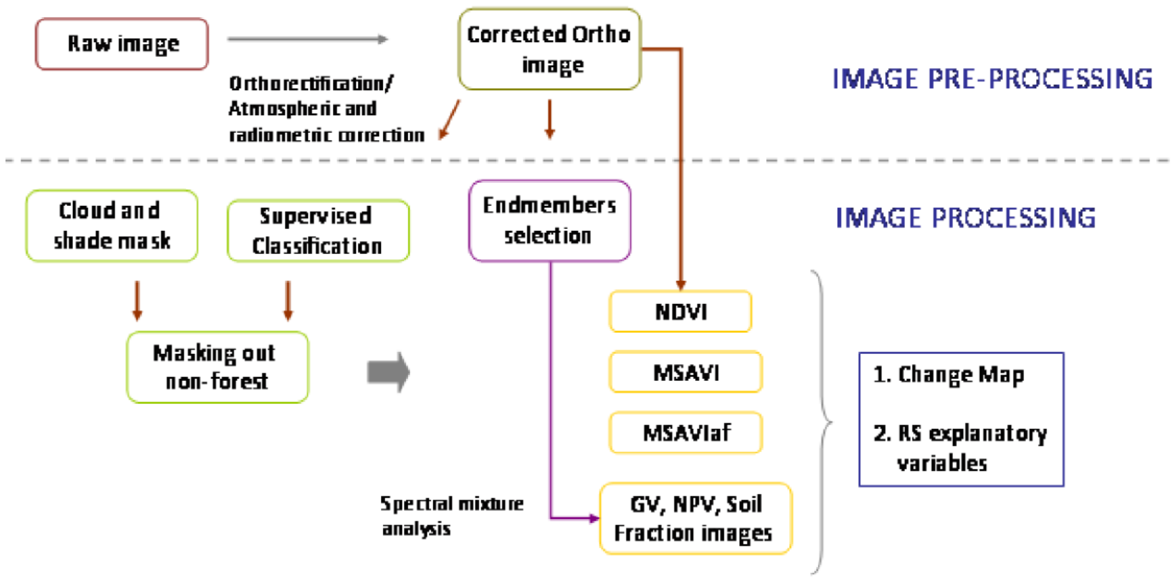

Figure 2. Schema of remote sensing analysis performed on each of the five images of the time series.

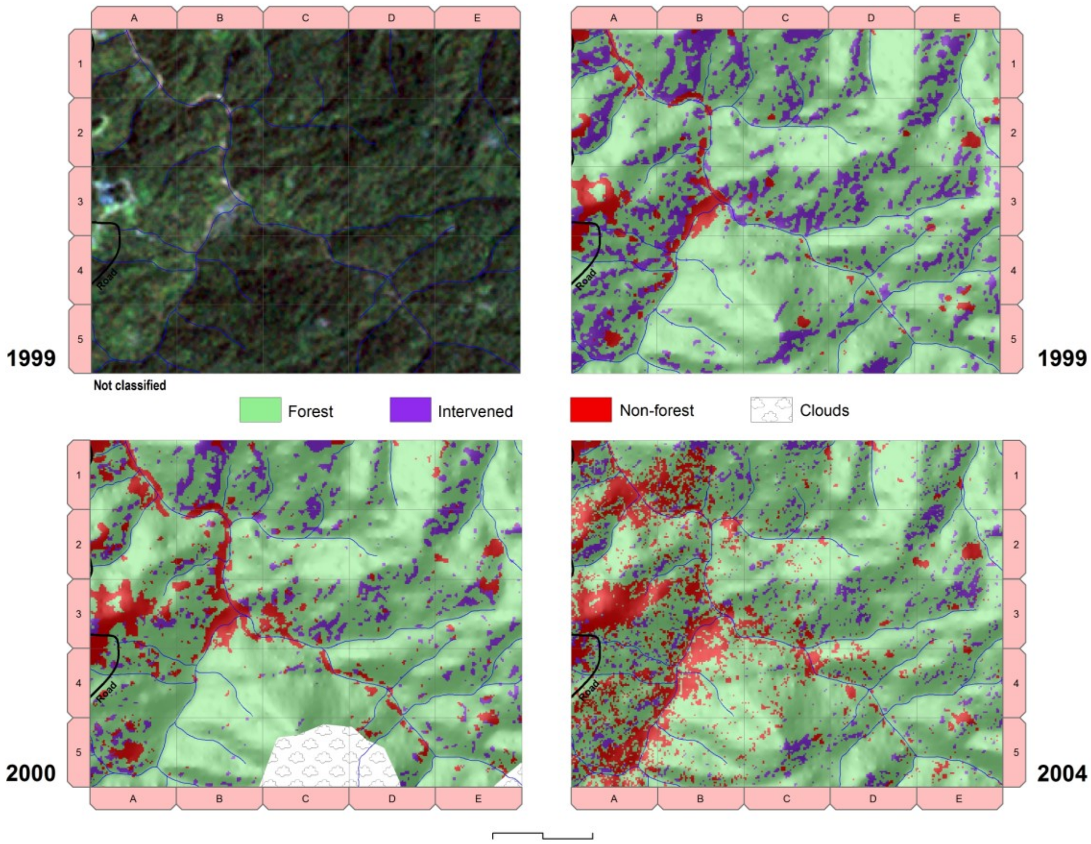

Figure 3. Map of forest cover change through time in the study area for the period 1999 (with the non-classified and classified image), 2000, and 2004.

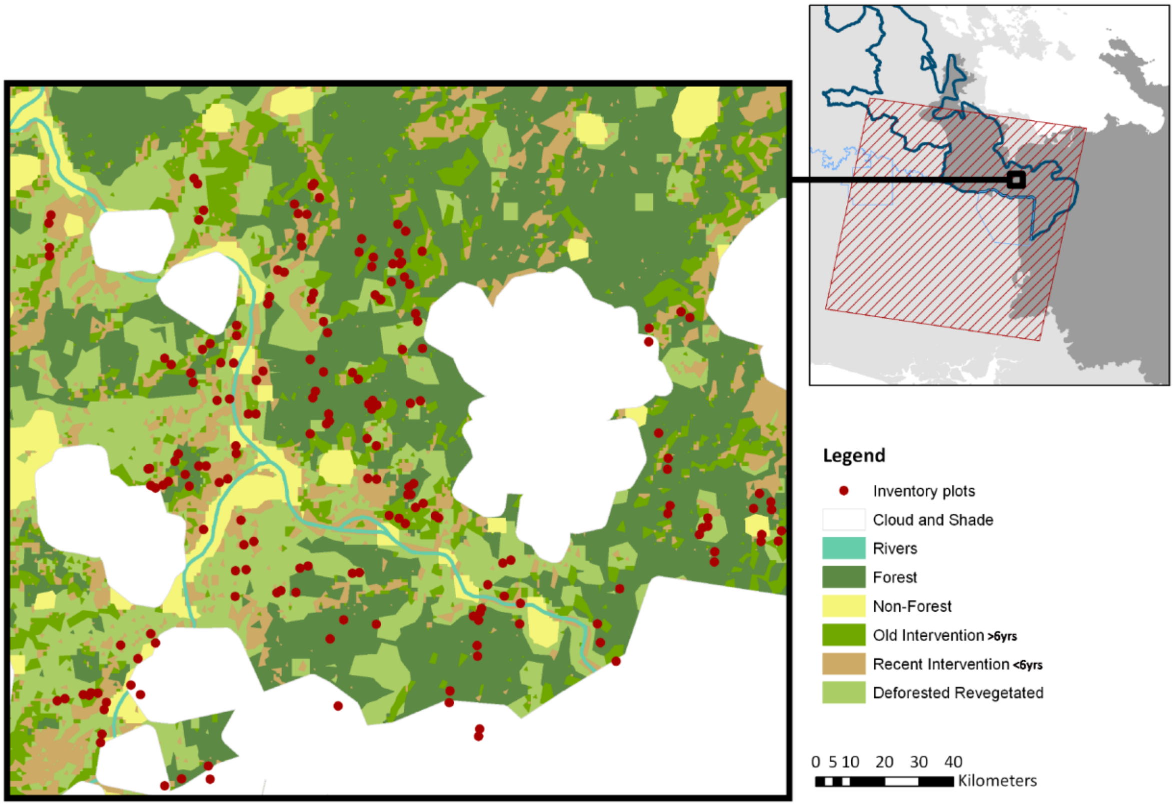

Figure 4. Forest carbon inventory area located in the Palo Seco Forest Reserve (blue contour) and in the Comarca Ngäbe-Buglé (dark grey). The closeup of the forest carbon inventory area shows the forest classes identified by remote sensing analysis.

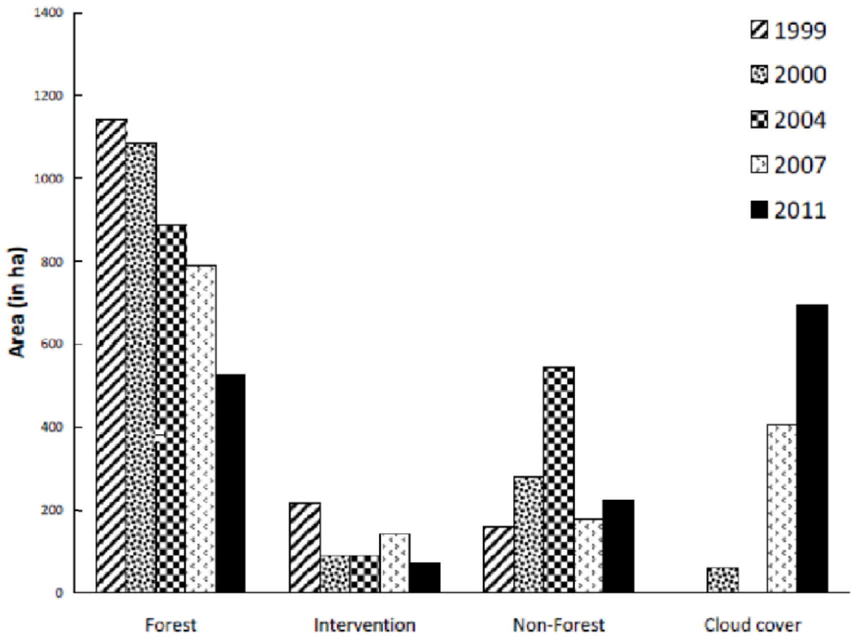

Figure 5. Forest area change over time from 1999 to 2011. The 2007 and 2011 images had a higher fraction covered by clouds.

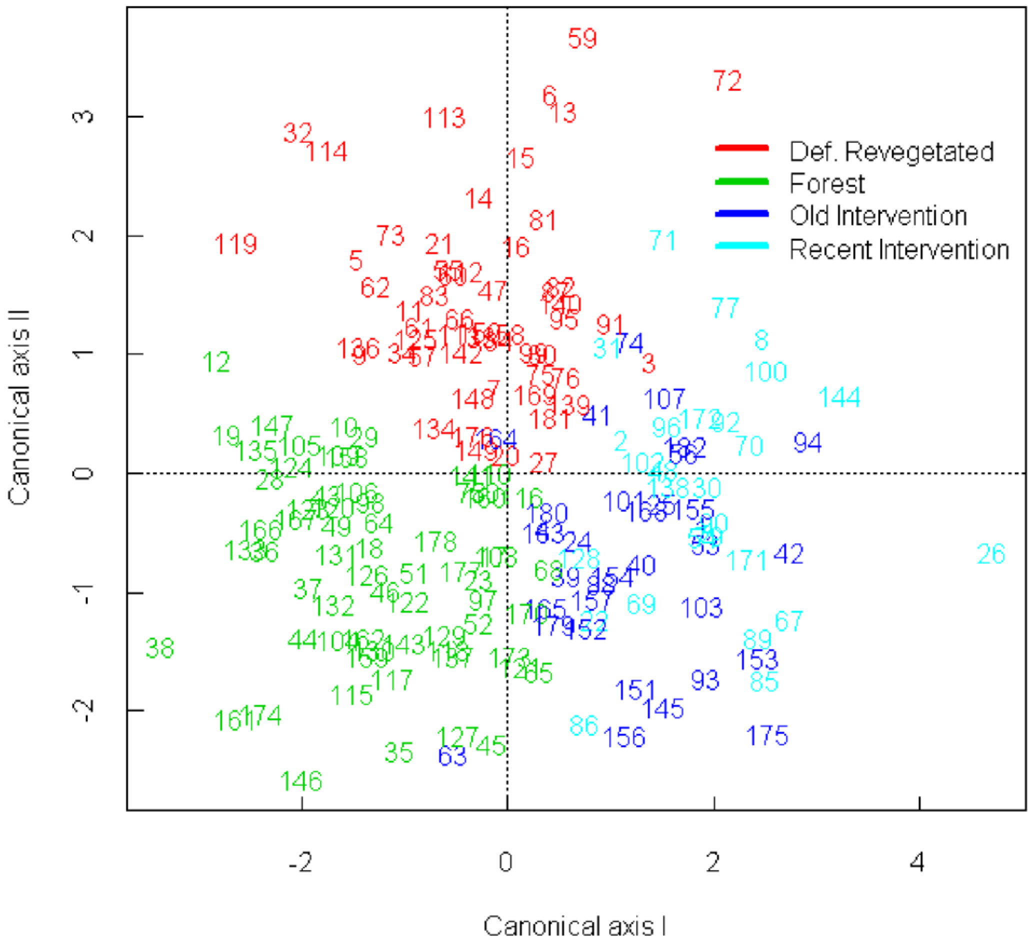

Figure 6. Ordination diagram of the sites, which are identified by their color group in the canonical discriminant space.

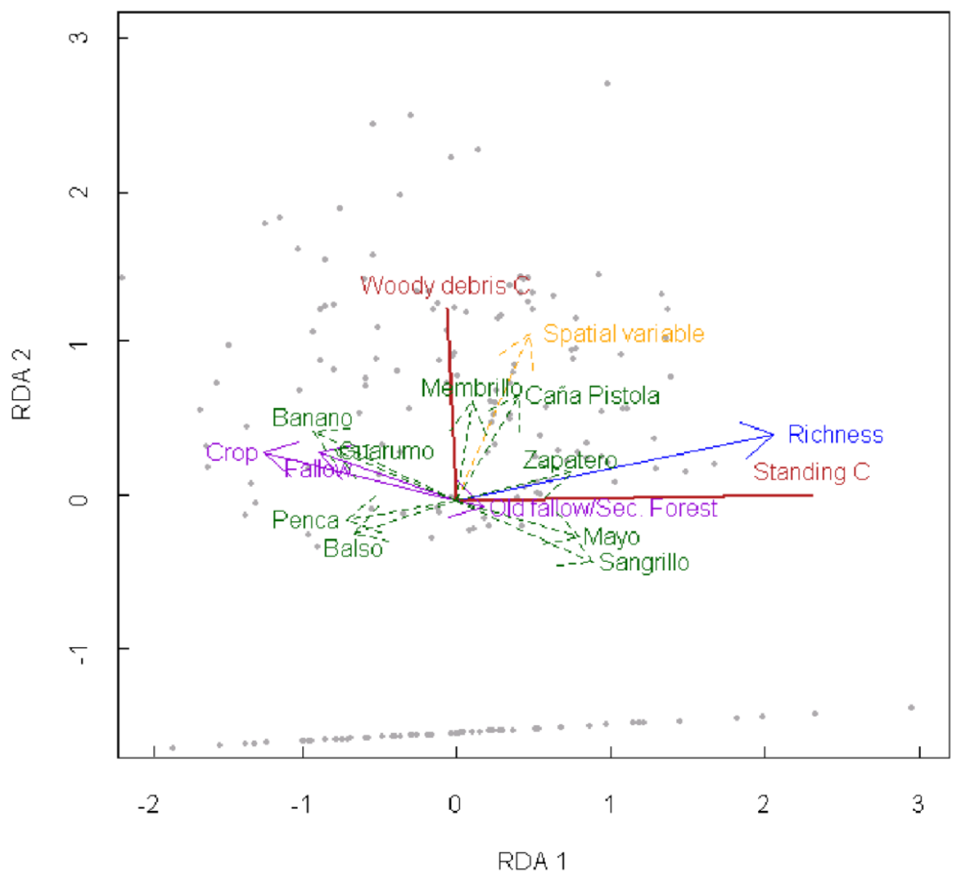

Figure 7. RDA ordination triplot of the above-ground standing carbon stock density (Above ground trees, palms, lianas, fern trees (Standing C); and Above-ground woody debris (Woody debris C) explained by the species richness, land-use (4 factors, k-1 are displayed), the identity of the dominant tree species (58 factors, main ones are displayed), and the db MEM variable (Spatial variable), scaling type 1. The pointed arrows represent the biplot scores of the explanatory variables. The red arrows represent the response variables. The linear pattern observed at the bottom of the figure is explained by the absence of woody debris in the plots sampled. Both canonical axes are significant at $p<0.001$. The first axis (related to standing C) explained 77.2% of the variance, while the second axis (related to woody debris) explained 22.8% of the total variation explained.

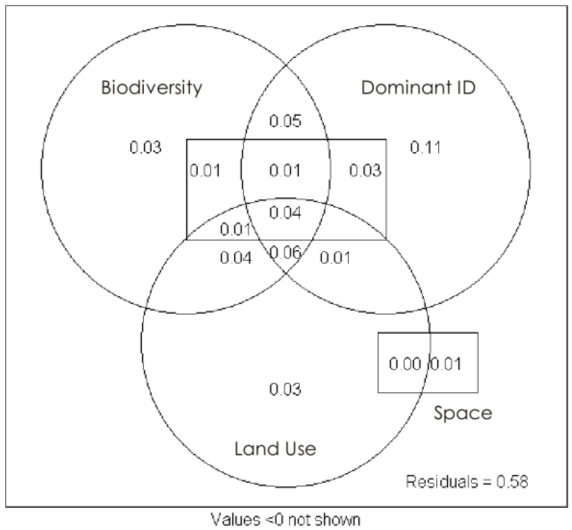

Figure 8. Venn diagram of the variation partitioning following the rda model using four variables (Land Use, Dominant Identity, Richness and Spatial variable) to explain the variation in the above-ground standing C and woody debris C. The rectangles represent the spatial variable.

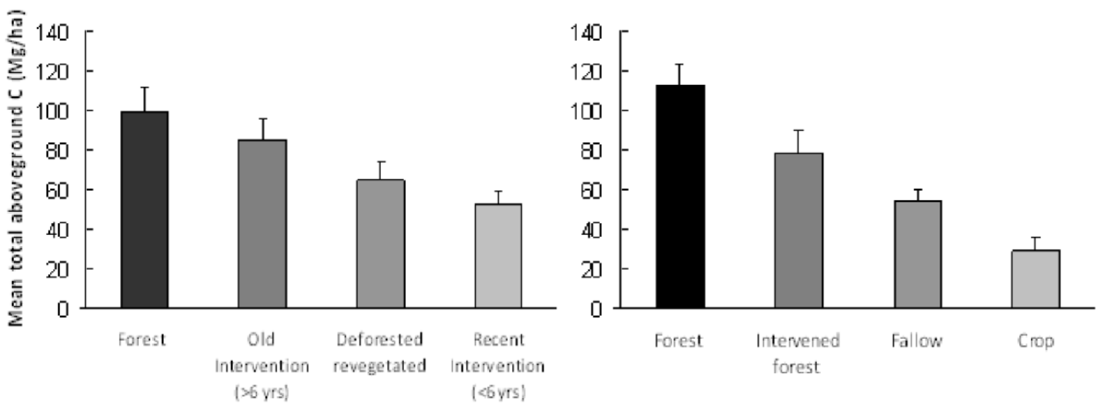

Figure 9. Mean total above-ground C stock (Standing C and Woody debris C) and standard error of the forest categories based on remote sensing (Left panel) and of the land-use classes based on ground survey (Right panel).

Linking statement 4

While Chapter 3 focused on land use related to shifting cultivation and its impact on forest carbon density and biodiversity in Palo Seco Forest Reserve, in the following chapter I take a new stance to inquire about the perception that land users in the area have of forest conservation. In Chapter 3 the field work was developed using a participatory methodology. Furthermore the community's insight into land-use practices was invaluable. This context raised my interest to engage with the local people and learn regarding the challenges of forest conservation. In effect, Palo Seco Forest Reserve is a protected area that contains a large population of mainly indigenous inhabitants who depend on natural resources for their livelihood. Using mainly structured interviews and focus group activities, I explore the views of local inhabitants as well as the perceptions of institutional stakeholders regarding the challenges of harmonizing conservation interests and social interests. Lessons for a successful implementation of REDD+ were extracted linking this Chapter to the general objective of the thesis.

CHAPTER 4:

Living Inside a Protected Area: Lessons for REDD+ with a Case Study from Panama

Status: Pelletier, J., Gelinas, N., Potvin, C. Living inside a protected area: lessons for REDD+ with a case study from Panama. *In preparation*

ABSTRACT

The Reduction of Emissions from Deforestation and forest Degradation (REDD+) mechanism currently being elaborated provides a new avenue to strengthen the management of protected areas where forest loss continues to occur. This study proposes a bottom-up approach by providing the much needed input of local perceptions of forest conservation which are crucial in order to tailor an effective and successful strategy for REDD+. Our study takes place in Palo Seco Forest Reserve, located in Western Panama which is the protected area experiencing the highest rates of forest cover change of all protected areas in the country and is characterized by a complex social, environmental, and institutional context, including a large resident indigenous population that could be described as economically poor, and that depends on the access and use of natural resources for their livelihood. To support a strategy that will promote forest conservation, it is primordial to take the perceptions of local residents into account to identify constraints and possible synergies between forest conservation and local livelihood improvements. The main constraint identified by this research is on food security, an overarching determinant of forest cover change for local residents, but a facet that has been largely unexplored in REDD+ literature. This research pinpoints the necessity to clarify legal rights in order to build trust and enable collaboration with local residents. This study provides an important input from the people living in Palo Seco forest reserve, and from other stakeholders, on possible strategies for maintaining forests for REDD+ while improving livelihoods.

INTRODUCTION

A policy framework for the reduction of emissions from deforestation and forest degradation (REDD+) was agreed upon by the international community at the 16th Conference of the Parties (COP-16) of the United Nations Framework Convention on Climate Change (UNFCCC) in Cancun, Mexico. The agreement aims at “slowing, halting, and reversing the loss and degradation of forests in developing countries” as a way to mitigate climate change through five main activities including reducing deforestation, reducing forest degradation, sustainable management of forests, conservation, and the enhancement of forest carbon stocks (UNFCCC, 2010b). One of the oldest solutions to prevent forest loss has been the creation of protected areas. Effectively, protected areas now cover 217.2 million ha (19.6%) of the world’s humid tropical forests and contain 70.3 petagrams of carbon (Pg C) in biomass and soil. Various studies comparing forest loss inside and outside or using matching methods to control for possible bias have shown that protected areas as well as indigenous lands can be effective at reducing deforestation (Andam et al., 2008; DeFries et al., 2005; Joppa et al., 2008; Nelson and Chomitz, 2011; Nepstad et al., 2006). Nevertheless, although protected areas may reduce rates of deforestation compared to surrounding areas, some forest loss often lingers. Scharlemann *et al.* (2010) estimate that 1.75 million ha of forest were lost from protected areas in humid tropical forests between 2000 and 2005, causing the emission of 0.25-0.33 Pg C.

Encroachment occurs because protected areas might not have an effective control of their boundaries (Ostrom and Nagendra, 2006), especially in the face of insufficient funding, low management capacity, corruption, political instability, and conflicts or lack of political buy-in (Curran et al., 2004; Naughton-Treves et al., 2005). The management of protected areas in the tropics is challenged by the fact that 70% of them have a resident population within their boundaries (Terborgh and Peres (2002). At times, local residents have helped detain deforestation. Nelson and Chomitz (2011), for example, found that multiple-use inhabited protected areas were in general more effective than strict protected areas at reducing fire incidence used as a proxy of deforestation. However, there are several examples across the globe of protected areas where substantial conflicts with local communities are threatening the long-term sustainability of the conservation programs and of forest resources in particular (Ostrom and Nagendra, 2006; West et al., 2006). Concerns have been raised about the possible negative impact of protected areas on the livelihoods of local communities through a loss of rights, exclusion from the use of natural resources, and displacement (Adams et al., 2004; Cernea and Schmidt-Soltau, 2006). Many authors agree that local communities bear the highest cost for the establishment of protected areas, while the greatest benefits are felt on a regional, national or international scale (Balmford and Whitten, 2003; Ferraro, 2002). There is an ongoing debate about whether, or to what extent, protected areas can help or harm the people in and around them (Brockington et al., 2006; Naughton-Treves et al., 2005), with recent research showing that while people living in protected areas may be poorer compared to national averages, there is not a causal link between poverty and protected areas (Ferraro et al., 2011; Naughton-Treves et al., 2011; Upton et al., 2008; Wittemyer et al., 2008).

For the purpose of this study, we adopt the viewpoint of DeFries et al. (2007) who stressed that the management of protected areas must consider peoples' needs and aspirations for use of land and other resources, particularly where people depend on these resources for their livelihoods, because gaining support from local populations is critical for sustaining conservation.

It is hoped that REDD+ might offer an avenue to strengthen the management of existing protected areas in order to reduce ongoing deforestation within and surrounding their borders (Ricketts et al., 2010). However, the need to balance social interest and human needs with conservation interests remains (DeFries et al., 2007). Because only limited empirical data has illustrated the perceptions and interest in forest conservation of local people living inside protected areas (Sodhi et al., 2010) we sought the input of local residents to understand the constraints associated with life inside a protected area as well as the opportunities that it brings to identify possible synergies between protected areas and REDD+. Our objective was to study local perceptions regarding forest conservation, keeping REDD+ in mind, by learning from 1) the experience of living in this protected area, 2) community interest in maintaining forests, and 3) ways to contribute to maintaining forest and improving livelihoods.

The research was conducted in western Panama in the Palo Seco Forest Reserve (*Bosque Protector de Palo Seco (BPPS)*), a protected area which shows significant levels of deforestation inside its boundaries and was identified by the National Environmental Agency (ANAM) as a priority area. With 65 protected areas representing 34.4% of the country (ANAM, 2006), Panama's national system of protected areas (SINAP) is extensive and the primary strategy used by the government to protect the country's forests.

RESEARCH AREA AND METHODS

Site Description

Palo Seco Forest Reserve was created by Presidential Decree 25 in 1983 to counter-act "a strong colonization, occurring in a chaotic and spontaneous manner, and threatening to destroy forests in the area" (Gaceta Oficial, 28 de septiembre de 1983) (Figure 1). In the years preceding the creation of the Reserve, the state had promoted a nearby hydroelectric-dam project, the construction of the Puerto Armuelles-Chiriqui Grande pipeline and that of the trans-isthmus highway that would connect Bocas del Toro province to the rest of the country thus facilitating access to a large extent of previously isolated forests. The BPPS has an estimated extension of 167,410 ha with a mountainous relief and an elevation generally > 200 m above sea level (ANAM/CBMAP, 2006). It serves as buffer zone for the La Amistad Biosphere Reserve and is part of the Mesoamerican Biological Corridor conservation initiative (*Corredor Biológico Mesoamericano del Atlántico Panameño*- CBMAP). BPPS corresponds to IUCN management category VI (1994), that is a multiple-use area where "further than contributing to natural resources and ecological systems protection, it is to contribute in a significant part to the social economy as a resource provider" (ANAM/CBMAP, 2006; IUCN, 1994).

In 1997, about half of the BPPS was incorporated into an indigenous reserve, the *Comarca Ngäbe-Buglé*. Legally, land inside the Comarca is inalienable and cannot be segregated, however only the usufruct natural resources are granted to indigenous people (Wickstrom, 2003). The country maintains its right to explore and exploit natural resources in the Comarca, including mining and use of water (Asamblea Legislativa, 7 de marzo 1997). Inside the Comarca land tenure is collectively held by kin groups, with rights of use inherited equally by women and men (Young, 1971). Between 1992 and 2000, the Comarca was the territory with the highest annual rate of deforestation in Panama(-2.3%) (ANAM/ITTO, 2003).

Thirty years after the creation of BPPS, the population living in the protected area is roughly evaluated at 30,000 (J. Mosaquites, *personal communication*), with the majority being indigenous, either Ngäbe (82%) or Naso-TjërDi (14%), as well as Latinos (4%) (ANAM/CBMAP, 2006). The annual population growth (2000-2010) for the Bocas del Toro Province and the Comarca Ngäbe-Bugle was 3.46% and 3.60% respectively (Contraloría, 2011). Overall, residents can be described as economically poor and largely dependent on natural resources. Shifting agriculture is the main source of livelihood for most Ngäbe families. Cacao agroforestry plantations are used for both household consumption and as the main cash crop. Cattle ranching is also common. An important proportion of the population living in the periphery of BPPS cultivates land and extracts forest resources from within BPPS (ANAM/CBMAP, 2006). The main drivers of forest cover change are: i) strong land occupancy for farming ii) selective extraction of resources, and iii) potential hydroelectric and electric transmission projects (ANAM/CBMAP, 2006). Approximately five hydro dam projects are currently in different stages of completion (ANAM/CBMAP, 2006) and more proposals have been submitted. Two colonization fronts are also active, stimulated by different agents: 1) Mestizos or Latinos of Chiriqui Province, moving from the continental divide to the Caribbean side and 2) Ngäbes going upstream towards the Cordillera to open access forested land.

Methods

Community Consent and Participation

The community where the study was conducted was selected after various visits to BPPS with the National Environmental Authority (in 2007 and 2009) due to its ease of access and openness of the community to participate. Permits were obtained from the government and the traditional authority of the *Comarca Ngäbe-Bugle* Indigenous Reserve. Six workshops on climate change, forest and climate change, and REDD+ were offered starting in September 2009 as a way to inform the community regarding the general context of the research to be conducted. Workshop attendance was consistently high (>45 people) for the duration of the study. All workshops were interpreted from Spanish to Ngäberé and facilitated by a Ngäbe teacher with experience in environmental awareness. After completing this series of informational workshops, we explained the objectives, methodology, potential risks (and actions to mitigate them) and benefits of the research project and formally asked for the community's consent to participate in research activities including a population census and mapping, a forest carbon inventory, and focus group discussions and interviews. The forest carbon inventory was conducted in 2010 (Pelletier et al., *submitted*) followed by the present study focusing on the community's perceptions.

The community selected three members to work with JP on household interviews. These three paid research assistants were trained during a three-day period to ensure familiarity with the research objective and significance of each interview question. Ethical considerations associated with conducting interviews were part of the training. The interviews were conducted in Spanish and Ngäbere, special attention was paid to ensure comparability of questions between these languages.

Population Census

A population census and mapping was performed to determine the number of residents, the main land-uses, and the geographic distribution of the different households. A participatory mapping exercise was first carried out in community workshops to identify the main landscape features and land-uses. Then, we performed a population census and georeferenced the location of the 67 primary houses, 48 in the main village and 19 in a nearby hamlet in the process of officially becoming a village. The sociopolitical structures amongst Ngäbe have remained decentralized and entwined in kinship networks (Bort and Young, 1985). Because the two areas are highly related by kinship we consider the two areas to be a single sampling area. Various copies of the population census and maps (participatory as well as georeferenced land-use and household maps) were given back to the community.

Focus group activities

A first focus group (March 2010) was organized with the community elders (only men attended) in order to recover the community history and derive a timeline of the main changes since the community was founded. Four additional focus groups (two with women and two with men) were organized to stimulate reflection on changes in terms of resources including forest area, fallow area, crop area, population, number of cattle, employment and cash income, water access, and health (Evans et al., 2006; Kumar, 2002). Participants were invited to quantify these changes using pebble scoring from the founding of the village until a projected vision of ten years in the future. Two focus groups (1 with women and 1 with men; August 2011) were held, where participants were invited to identify the community development priorities and provide insights on how they could be achieved (Wollenberg et al., 2000a; Wollenberg et al., 2000b).

Household and Key Stakeholder interviews

A questionnaire was developed to understand 1) household characteristics, 2) land-use practices, 3) perceptions of the protected area, 4) institutions, 5) perception of forest cover change, and 6) ways to maintain forest and improve livelihood. A total of 50 interviews were conducted in August 2011; 45 in the communities with the research team using a structured questionnaire with mostly open-ended questions and 5 in-depth interviews with key stakeholders from the government and the Comarca Ngäbe-Buglé, hereafter called ‘institutional participants’. Participant selection (67% of the total household) reflected the willingness to participate, the availability of informants, and the research time available. Each household was first visited to briefly explain the objectives of the study and set up an appointment if they were interested. Before the interview, the objective of the study, the risks (and how to mitigate them), and the benefits were restated to the household representative and any questions about the research were answered. Oral consent was obtained in all cases. Interviewees were asked for permission to tape record the interview; 21 household participants and all other institutional participants accepted. Detailed notes were taken in all cases. Fifteen women and 30 men were interviewed. When both men and women were present for the interview, the women’s participation would often be attenuated.

Data Analysis and Validation

Qualitative data analysis was used to identify common themes, compare perceptions in a consistent manner, and establish cross-relations Verbatim was coded using N-vivo software. Insights gained from participant observation and from key informants were used to validate results from household interviews. Triangulation also used land-cover maps, interviews with institutional participants, the forest carbon inventory, and focus group activities. Statistical analysis was used to test hypotheses in case of divergent positions and to validate conceptual models. Multivariate statistical analyses were used to unveil relationships between household characteristics and livelihood activities using Principal Coordinates Analysis (PCoA), and clustering techniques. Differences in perceptions (coded as dummy or categorical variables) were tested among household clusters or landholding size groups using linear discriminant analysis. A chi-square test was used to determine the differences in the number of small (<10ha) and large (≥ 10ha) farm sizes adopting cattle ranching, replanting on the same plot, working as *peon* (a laborer) as well as differences in perception (categorical or dummy) between men and women of living in a protected area. We estimated the correlation between farm size and forest area on the farm and used regression analysis to examine the relationship between farm size and fallow period. Analysis of variance (ANOVA) was used to examine the effect of age class on farm size.

RESULTS

Land-Use Practices and Livelihood

According to the timeline focus group, the studied area[8] was colonized in 1975 with an expedition including twelve men who were later followed by their wives and children. This occurred before the construction of the trans-isthmus highway and pipeline and prior to the establishment of the BPPS. These migrants were "moving away from an overcrowded area, starvation, and sickness" found in the vicinity of the Cricamola river delta. The founding families and other early newcomers, including their direct descendants, nowadays generally possess the largest land holdings and land distribution is skewed, ranging from 0 to 210 ha (Table 1). The size of the land holdings has a series

[1] Names are not divulged to protect anonymity.

of implications that are synthesized in Figure 2. In effect, it was found that on average younger households have a smaller farm size ($F=4.63$, $p=0.0069$). We found that landowners with smaller farms (<10 ha) do not have cattle ($X^2=6.18$; $p=0.0196$), they work significantly more on other people's farms as a *peon* ($X^2=13.85$; $p=0.0015$), and replant significantly more frequently on the same plots ($X^2=7.1529$; $p=0.0226$). Many interviewees claimed to not have enough land to maintain cattle. Smaller land holding is generally associated with shorter fallow period ($R^2= 0.19$; $p=0.0030$). We also found a significant correlation between the landholding and the quantity of forest owned ($r=0.95$; p-value = 2.2e-16). We found no statistical relationship between household and livelihood characteristics and perceptions.

One of the main features of household economy is the reliance on subsistence agriculture by all households and the assistance from government programs including the *Red de Oportunidades* and Universal (education) grants by the large majority of households. Since 2006, the *Red de Oportunidades* provides a conditional cash transfer of US$50 per month per household to women heads of households in situations of extreme poverty (MIDES, 2012). All households interviewed have received the Universal grant Program since 2010 which delivers US$180 annually to each Panamanian student for general basic education. A large number of households are involved in agricultural production either by cultivating cash crops (mainly culantro) or by selling surplus production while cattle ranching is of lesser importance (Table 2) The products cultivated include different varieties of bananas, *fifa* (peach palm), *dashin*, *ñame* (yam), *ñampi*, *yuca*, *fruta pan,* and corn. Surplus is sold on the main road to individuals or middle-men as well as in the closest town.

The majority of interviewees clear forest or fallow before planting (Table 3). The aggregate cleared area of forest or fallow reported in 2010 is > 17 ha, almost entirely for subsistence agriculture. The majority of informants prefer to use fallow for planting, with the shared observation by participants that "you need to clear forest for the land to produce". The length of the fallow period varied substantially between farmers, with a maximum fallow period of 10 years (Table 3). Fire is not part of the common land-use practices however purposeful fire has been used for the creation of pasture area in one of the villages. Because no true dry season exists, vegetation cleared for new farms is usually not burned, but rather left to decay in the field, a system also called slash-and-mulch that has been described elsewhere on the Caribbean slope of Western Panama (Smith, 2005). Some households favor permanent rather than slash-and-much cultivation, either by choice to conserve their forest (50%), because their plots are far away, or because they have no choice since their plots are small and/or they have no forest or fallow to clear. The use of pesticides and chemical fertilizer is almost strictly associated with culantro production alone.

Perception of Deforestation

This section regards participants' perception of forest cover change recorded in focus groups and interviews in reference to rule-making for the management of forests and institutions related to the access and use of forest resources and the factors that increase deforestation.

Participants in the focus group activities agreed that, through time, forest cover decreased while fallow areas increased (Figure 3). They identified a period (late 1980's) of important cattle ranching, ending after the influx of a disease that killed almost all the cows. Forest cover increased after the epidemic due to the abandonment of pastures. Secondary forests on abandoned pasture land were in fact visited on the field during the forest carbon inventory. The focus groups noted a decrease in agricultural production, with either less cultivated areas or less food available. They also recorded a perception of diminishing water levels, either for consumption or when washing clothes ("the river has gone down").

Based on the interviews, 48.9% of participants perceived a decrease in forest cover, 37.8% perceived a limited change in forest cover, and 13.3% perceived an increase in forest cover. Five out of 6 participants perceiving an increase in forest cover were not born in the area and arrived in the 1990's. Of those observing no change in forest cover, some expressed the view that fallow was replacing forest with no net change.

Opinions expressed by institutional participants from the government and the Comarca regarding perceived forest cover change in BPPS area differed considerably. Government participants considered deforestation to be the main problem in BPPS, "if they ask me what is the main environmental problem in Palo Seco, I would say it is deforestation", while two *Comarca* participants considered that there is a low level of deforestation in the *Comarca*, "in the Comarca there is not a lot of deforestation, they only utilize the area or plots for eating, they clear in order to survive".

To understand rule-making and the role of different institutions in the access and use of natural resources, scenarios were presented to community participants during the interviews. Villagers' perceptions of land-use decisions, community rules, and conflicts were thus recorded. Despite the collective land tenure in the Comarca, decision making about the forest use appears to rely on the individual land user. Only 24.4% of the participants judged that the community would be allowed to say something if someone cleared many hectares of forest or sold timber from their land. The internal rule of the community is "each person is responsible for their own land". Some responded that it would not be fair, "why does he have this opportunity and not me" or again "for me it is prohibited, well I am going to clear too". Many participants suggested however that the community could not say anything but that they would personally denounce these actions to ANAM. Several participants mentioned their preoccupation; "[those who deforest] will end up without trees, there will be no hope for the family (the children), there will be no more forest. One can only try to talk to the person". In effect, forest owners affirm maintaining forest primarily for their children who will need land to cultivate. Participants were also asked what they would do if a neighbor cleared forest on their land. One third of the participants indicated that they would turn to the alderman who represents the community's internal law and is elected in community assembly and/or to the Comarca authority, while an equal number invoked either ANAM or the 'law' without specification. Conflicts in the community were reported by 53% of the participants. All conflicts cited by participants were related to the access to and use of natural resources. According to an institutional participant "[conflicts] are proportional to the number family members and related to the land available" and they are "more frequent for inherited cultivated land". The role of the Comarca authority in solving conflicts was also acknowledgement by this institutional participant: "There are more conflicts outside the indigenous reserve [between Ngäbes]. At least in the *Comarca*, there is a Ngäbe legal framework and it is recognized legally and traditionally in Law 10."

Participants identified ANAM as the main entity responsible for the ongoing deforestation in the protected area because ANAM would not monitor and enforce the law as it should to halt deforestation (Figure 4) "There is a law so why is there clearing? […] ANAM has to solve this problem for us. They have to be more present in the area to monitor". They also stressed that ANAM was not reacting to forest clearing caused by the *Campesinos*: "they clear, they do not obey the law and ANAM does not do anything" or again "Latinos are smooth talkers so ANAM does not fine them". These Latino farmers located close to the road would be responsible for forest clearing for cattle ranching according to the majority of the respondents, "they do not respect the law [of the protected area]".

Institutional participants also discuss the institutional weakness of ANAM as a factor to increasing deforestation: "Without any structure of government officials and without the necessary resources to be able to face and manage a protected area and we continue with this same policy, it will surely be the first factor that will contribute in the coming years to continued deforestation". In effect, ANAM in its annual statistics report (2011) indicates that only 3 park rangers have been assigned to the protection of the area which represents >55,000 ha per ranger. What's more, all three rangers are not on duty 24hrs/7 days a week. The total operating budget or payroll of the protected area is US$ 20,400/year and the total investment budget provided by the Fideicomiso Ecológico de Panamá (FIDECO) is around US$9,451/year (GEF, 2005; Mosaquites, 2008). An investment of US$26,873 in infrastructure was made over the 2007-2008 period (ANAM, 2008). In order to improve environmental protection a management plan was created for the protected area, financed by the CBMAP project, but it was not implemented, perhaps because a great part of the funds were to be derived from Payment for Environmental Services (PES) a system that was never achieved and for which payments were to be received from the Hydro-dam companies (ANAM/CBMAP, 2006).

The lack of political commitment is also underscored by this institutional participant:

> "If you prioritize something, you invest in it. The national government does not have the will to prioritize the environment and to invest in conservation. […] The national government has given

> itself the right to administer and manage protected areas and in a centralized manner even… this type of policy […] will only result in more deforestation and the destruction of natural resources”.

Finally, in the opinion of participants, the factor posing the greatest challenge with maintaining forest cover will be population growth (Table 4). Participants in the focus groups observed and forecasted a steady population increase. Women also indicated that governmental assistance including the *Red de Oportunidades* and Universal grants stimulates families to have more children. “It is population growth that forces us to clear more forest, it is inevitable, and there is no solution”. The national population census indicated that in the district the population almost doubled between 2000 and 2010, passing from 2,264 to 4,129 individuals (Contraloría, 2011). The adoption of cattle ranching is also perceived as an important contributing factor to increase deforestation. Some people in the community are interested in this practice and value this asset “…the cattle that we have are so [the children] can learn and as an inheritance for our children” while others are against it “It is not possible [to have cattle], if I would raise cattle, the whole forest would be chopped down”. Immigration to the area and the lack of education and institutional support were also the main factors mentioned that would augment deforestation.

Living in a protected area

We sought to record the perception of participants regarding living in a protected area, including the positive and negative aspects, and examined how the enforcement of protected area legislation by the environmental agency affected local residents’ opinions. The majority of the participants (73.3%) think that it is generally fine to live in the Reserve with only a few informants 6.6% thinking that it is entirely negative with no statistical difference between men and women. Access and availability of natural resources appears to be the most important benefit offered by the protected area including access to a river and clean drinking water, building materials, firewood for cooking, a clean environment, and game hunting (Table 5). In BPPS, “there is enough land, for the climate, the sun is not as hot as in lower lands. Here you can collect firewood nearby, and I like to watch the monkey jumping about, these are the reasons I like living here".

All the negative aspects of living in the protected area mentioned have to do with restrictions and control of the access to natural resources by ANAM (Table 6). The main negative aspect is the restriction on clearing forest for agriculture (93.3% of participants) which directly impacts food production. Cultivation of the same plots over time results in decreasing yields and 64% of the participants noticed a decrease in production, 75.6% indicated that they would need to clear more land and 86.7% that they need to clear forest to maintain food production. These perceptions are echoed in the literature, where challenges with shifting cultivation and population growth inside the Comarca linked to decreasing levels of productivity and resource scarcity have been reported, as well as economic adaptations towards the cash economy (Bort and Young, 1985; Young and Bort, 1999; Young and Bort, 1995).

Institutional participants also perceived negative aspects for local residents of BPPS, "in order to work on their land they have to go to ANAM, ANAM tells them what they have to do to be able to do their work; or if they don't [consult ANAM], the institution comes right away to stop it because there is a conservation law."

The enforcement of the protected area legislation directly affects the livelihood of community participants. We catalogued 13 cases of law enforcement by ANAM. Twelve cases out of 13 were for subsistence agriculture and one was for hunting for subsistence but none was for commercial purposes, "I received a visit from a park ranger; it was about 4 years ago. I was clearing old fallow to plant bananas, he came to forbid me […] he told me to stop if I did not want to go to jail, so I stopped". One listed case from the community involved a resident going to prison for clearing forest prior to the creation of ANAM. Two cases of fines were mentioned before the 1998, one of US$50 that was never paid. From the institutional viewpoint, 4 out of 5 institutional participants said that no sanction were applied to indigenous residents of the protected area but only to outsiders, "Until now [sanctions] have not been applied because the Comarca authority says 'no, with indigenous people no' ". In addition, given the political and social context, it is difficult for ANAM to sanction an indigenous person within the Comarca:

> "How to apply a fine of fifteen hundred dollars to an indigenous person who does not even receive one dollar per day? How to apply it? How to apply or to punish an indigenous person for an environmental crime […] because logging in protected areas is an environmental crime, and environmental crimes are incorporated in the penal code in Panama […]"

Interestingly, our results highlight an apparent rift between, on the one hand the law of the BPPS Reserve and on the other hand the statements made by government officials and the resulting perceptions of local residents of what they can or cannot do inside the Reserve. In effect, BPPS's regulations prohibit cutting trees, burning (for agriculture, *quema*), hunting, and all agriculture or plantations that have not been expressly authorized by the environmental authority[9] for the sole purpose of the subsistence of families collaborating with forest protection (Gaceta Oficial, 28 de septiembre de 1983). According to this institutional participant: "Look at the signs in La Amistad National Park, it says logging prohibited, hunting prohibited, agriculture prohibited. And Palo Seco, same thing. So, what can people living inside BPPS do?" Interestingly, 57.8% of participants apparently agree and strongly affirm that being prohibited from hunting for food was a negative aspect of living in the BPPS along with cultivating, fishing, and firewood collection. However, these practices are not proscribed by the protected area legislation.

On the other hand, a governmental participant confirmed that "ANAM identifies cases of forest clearing almost entirely on the basis of denunciations". So, the management of the protected area depends on the good will and collaboration of local community members to identify violations.

The lack of coherence between the message given to communities based on a restrictive approach and the dependence by the environmental agency on local residents' collaboration is synthesized by this institutional informant:

[9] National Direction of Renewable Natural Resources of the Ministry of Agriculture -*Dirección Nacional de Recursos Naturales Renovables* (RENARE) was responsible of the administration until 1986 with the creation of the National Institute of Renewable Natural Resources - *Instituto Nacional de Recursos Naturales Renovables* (INRENARE).

> “ANAM does not use a policy of recognition that they have rights to access and use natural resources. ANAM uses a more restrictive policy; the type of management that has failed, but that persists”.

Despite the enforcement role of ANAM and the apparent lack of coherence between the message sent to communities and the actual legislation of the protected area, half of the community participants thought that the relation has improved with ANAM while one third thought that it was the same as before (“they apply the same law”). The majority thought that the relation was fair, less than on third think it is good and the rest see it as poor. Improvements in the relationship are explained with “ANAM has let us work [clear forest for cultivation] more”, “ANAM permits selling wood outside and for personal use”, “ANAM has given us opportunities including some projects for the community” or “ANAM does not yell too much”.

Maintaining forests: alternatives proposed

Actions taken to conserve the forest have been reported by the community and important lessons can be learned from proposals enounced by interviewees for participating in a project to maintain forest cover.

The synthesis of information delivered by participants on the actions taken by the community in order to conserve forest show that: 1) the majority of informants maintain forest on their land; 2) forest conservation depends on the landowner’s decisions; 3) Some landowners do not need to clear forest, “I can conserve forest because I have enough fallow to work on”; 4) the majority conserve for the future and as an inheritance for their children; and 5) Some conserve forest for different reasons including to protect materials and hunting grounds, to teach their children about the forest and animals, to work on it later on, and because of the law.

The various projects that have been implemented in the community including plantain and *otoe* farming, fish ponds, a handcrafting house, and poultry have generated some limited success and some failures according to participants. Projects with continued technical support have had higher rates of success.

We asked community participants about their opinion on the importance of taking action to counteract forest cover change. A full 91.1% of them think it is important to maintain forest and 82.2% that reducing deforestation would be a good idea. Of those who did not think reducing deforestation is a good idea, participants mentioned that "there is already enough restrictions on us" or declared "I already conserve, I could not do more".

Ensuring food security is clearly the overarching criteria that each household will first evaluate before participating in a project or program to maintain the forest or that will enable them to participate in the long term. The general preoccupation for food security by community participants is illustrated by various criteria included in Table 8 including being allowed to clear for subsistence/ being allowed to cultivate for the family's well-being, allowing for clearing of forest for subsistence if necessary, providing security on what they will depend on, and in terms of benefits it needs to be sufficient to maintain the family or again, "have something to eat with the family". The dependence on agriculture for subsistence is illustrated here: "if [the compensation] is not sufficient for livelihood, we have to clear forest". The incentives mentioned to maintain forest cover were thus dominantly agriculture-based, largely for family consumption and also in a minor extent for cash crop production. Those participants favoring direct payment said that they would invest on their farm. Direct payment for on-farm investments could however generate a perverse incentive if it goes towards activities reducing forest cover: "With the money that the government will give me, I will buy cows to put on 2-3 ha".

Institutional participants recognized the need for incentives to the local community for maintaining forest. Nevertheless, three of the institutional participants tended to disagree or perceived the greatest risks with the direct payment option. The fact that collective land cannot be alienated complicates this option. Direct payments might promote land conflicts mainly on (informally) inherited land and amplify economic inequalities. One institutional participant believes that instead of contributing to create social capital in the community, direct payment would promote a paternalistic relationship of dependence and subordination towards the government.

Of the ways to maintain forest cover and improve livelihood, access to education for children, including secondary and higher level education, was proposed by various community and institutional participants in interviews. Education and the creation of a health center also ranked as the top priorities in focus group activities. Capacity-building for agricultural production was also proposed to help maintain forest and improve livelihood. In fact, very few individuals (2) claimed to have received training to help them produce. All institutional participants pointed out the need for environmental education in the communities. One of the *Comarca* participants stated to this effect that "there is a lack of environmental education coupled with social programs promoting accompaniment towards self-management production activities". Furthermore, one participant explained that in the indigenous reserve the activities should promote "cultural and social awareness", including for example working in groups and cooking together in order to keep the culture alive.

Of the alternatives proposed to maintain forest and improve livelihood, a structural problem with the convergence of conservation and social interest is identified by one institutional participant:

> "a serious problem we have in this country is that we do not have an institution to address poverty. You cannot address poverty with subsidies; you need to professionalize the care for poverty. […] If no one understands the complexity of poverty, if no one understands the complexity of harmonizing conservation interests with social interests… well, we will follow the same cycle."

Interestingly, various projects, including the Ngäbe-Buglé Project (PNB) and the *Corredor biológico* (CBMAP) have been simply abandoned. None of them was part of a strategy for directly maintaining forests; they aimed at reducing poverty and malnutrition.

DISCUSSION

A Missed Opportunity

One premise of this paper is that understanding local perceptions regarding forest conservation in a protected area suffering from deforestation, could provide important information for forest governance in other threatened protected areas and yield lessons pertinent to REDD+ implementation. A first important result is that a majority of participants expressed their support for forest protection, emphasizing that in other communities all the resources had been destroyed and that the protection granted by law to the forest inside the protected area made their village a better place to live. Our results nevertheless suggest a missed opportunity because the relationship between community members and the authorities in charge of the protected area is not collaborative and lacks the necessary incentives to promote forest conservation in this inhabited multi-use landscape.

Collaborative strategies have been promoted as a means of addressing problems associated with the management of social-ecological systems (SESs) (Berkes et al., 2003; Folke et al., 2002) A collaborative approach calls for a shift of paradigm based on establishing trust and legitimacy. Establishing such trust and legitimacy requires clarity of legal rights about who can access and make use of natural resources and who should be excluded from those rights (Ostrom, 1990). Exclusion should follow from simple and legitimate rules widely diffused. In developing countries, when the financing of protected areas is limited, monitoring of violations inside them often relies on denunciations of illegal activities by local residents. Yet, the message received by local residents make some subsistence activities, which should be permitted, illegal. Because ANAM has retained discretionary rights to give authorization to the "families collaborating with forest protection", ANAM can agree or decline this right to local users (Gaceta Oficial, 28 de septiembre de 1983). We observed that, for community members, perceptions that the rules set are unfair and that rights of access and use of forest and land are not clear, preclude trustful collaboration and stimulate a *laissez-faire* attitude.

The missed opportunity for forest conservation that could be had by collaborating with local residents in a more decentralized manner also stems from the lack of political will which is reflected by the extremely limited capacity dedicated to management of the protected area, including funding, material, infrastructure, and trained personnel. In reality, the difficulty to apply politically sensitive restrictions to poor forest-dependent residents and the lack of resources to effectively involve residents in forest management or just to secure a presence in the area, has led ANAM to fall into a tolerance policy, securing social peace based on free access and at times the inefficient use of natural resources. In effect, financial resources are necessary to establish fruitful collaborative management systems, to provide capacity-building, create space for joint decision-making, and grant incentives to local communities. Much remains to be done at this point in order to have forest dwellers take responsibility for the governance of the forest resources they depend on. However, at this point, the lack of political backing has been identified as one of the main obstacles to improving the management of the protected area.

Conserving despite the desire to "develop"

In Panama, and elsewhere in Latin America, new threats to forests come from infrastructure or extraction projects such as roads and mining. This is clearly mentioned in the REDD+ preparatory documentation submitted by various countries (e.g. Peru) to the Forest Carbon Partnership Facility of the World Bank (http://www.forestcarbonpartnership.org). State-led hydropower dams inside protected areas and on indigenous land is also exerting increased pressure on protected areas (Mascia and Pailler, 2011). Our case study brings forward an understanding of the hierarchy of interests that shape decision making regarding protected areas. Recent modifications to protected area legislation give us a glimpse at the role that the State attributes to the area for the country's development in spite of local residents. One of the greatest challenges that REDD+ will face will be the coordination of efforts to halt forest cover loss with the development agenda of local governments. Lessons on how protected areas have been impacted by such development policies could therefore be of considerable value.

Various legal changes have opened the door to infrastructure projects inside protected areas. In effect, in 2005 a new era began with a resolution (N° AG-0366-2005) allowing for private administration concessions in Panama's protected areas. The following year Decree N° 71 of the Ministry of Economy and Finance modified the legislation of BPPS (Decree N° 25) to allow activities of "social interest or benefit for the rest of the country" (Gaceta Oficial, 1 Junio 2006). In 2007, the Chan-75 hydroelectric project was declared of social and public interest and granted a concession and the construction was initiated a few months later (AES, 2012). The area impacted by the reservoir is 1,394 ha implying the clearing of approx 850 ha of forest and the relocation of various communities. Initiated without a full social impact assessment, communities affected by Chan-75, located in BPPS but outside the indigenous reserve, have brought the case to the Inter-American Commission on Human Rights (Fundación del Consejo General de la Abogacía Española, 2011). On June 18, 2009, the Inter-American Commission granted precautionary measures in favor of the Ngäbe communities for the purpose of preventing irreparable damage to the communities' right to property and to their security.

What are the lessons that can be learned from these events? The course of events unveiled by our case study highlights a top down approach to conservation (Oestreicher et al., 2009) plagued by unclear rules and conflicting interests by which ANAM restrains inhabitants from clearing forest for their livelihood while giving concessions to hydro-dam projects that result in significant forest loss. Local residents' apprehension of government-led infrastructure projects is palpable and will represent a significant barrier to REDD+ implementation.

Pro-poor policies for REDD+: food security

The ultimate goal of REDD+ is to mitigate climate change, yet more and more emphasis is being put on the accompanying safeguards (Murphy, 2011; UNFCCC, 2010a). These include environmental, such as biodiversity protection, and social safeguards such as the respect of indigenous rights and alleviation of poverty. Brown et al. (2008) have underlined the importance of designing pro-poor policies for REDD+, in order at least to 'do no harm'. As we know, agriculture expansion is the main cause of deforestation in the tropics (Geist and Lambin, 2002). Recent research has addressed the issue of agriculture intensification as well as agricultural production in general with the objective of reducing forest loss (Angelsen, 2010; Pirard and Belna, 2012).

Our case study emphasizes the perception that forest dwellers have of the importance of agriculture and food security. REDD+ should therefore be understood in the context of food security as more than 1 billion people worldwide lack sufficient dietary energy availability (Barrett, 2010). The importance of food security explains the opposition of local people towards the restrictions on clearing forest for subsistence agriculture. This issue will be prevalent worldwide since shifting cultivation is still the main land use in many areas of the world as well as being the corner stone of food security.

It is therefore important to base the REDD+ discussion on reality: which incentives can REDD+ substitute for daily sustenance? Food security is the main preoccupation of local community members and it is directly associated with the ability to maintain forest cover or not. Without improved agricultural systems allowing for maintenance of soil fertility and the necessary training of farmers, forest clearing is the only productive option. Incentives are likely not to be enough to compensate for the daily food intake. Past attempts to link social and conservation goals have often failed because "the alternative livelihoods created were often small compared with the income from deforestation and forest degradation, and the benefits were not made conditional on forest conservation" (Angelsen, 2010). If incentives are too small and that there is no action taken to meet people´s needs in terms of food production to secure food security, forest conversion to agriculture will continue.

The present situation of encroachment is not a guarantee of the future; the steady population growth will pose greater challenges and forest threats will continue to expand even in more remote areas (Green et al., 2005; Ricketts et al., 2010). Many of the villages founded before the creation of the BPPS were the result of out-migration from the Cricamola river delta. With village enclosure "the third generation will have to migrate elsewhere, as my parents did", possibly to other open access forests deeper in the *cordillera* of La Amistad Biosphere Reserve. With unequal land distribution, we can already see that small landholding in the village studied limits future prospects for these shifting cultivation farmers, leading to a poverty trap (Coomes et al., 2011) though this pattern is apparently not a result of the establishment of a protected area (Ferraro et al., 2011).

Furthermore, incentives to improve livelihood should be elaborated in a coherent manner, possibly with some revisions to the current governmental assistance programs. In the case of BPPS, *Red de Oportunidades* and Universal grants appear to oppose forest cover protection by stimulating population growth. Investments in the education system, prolonging education for girls which has been shown to delay the birth of the first child, would be a better option along with promoting off-farm employability.

In that sense, it is important that subsistence agriculture be allowed but also supported. Efforts to improve this subsistence agricultural system are needed, not only for large-scale agricultural intensification. Participatory land-use planning to balance human needs and maintain forest cover has been proposed as an adequate way to avoid harm, and move toward a collaborative framework with local communities.

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REFERENCES:

Adams, W.M., Aveling, R., Brockington, D., Dickson, B., Elliott, J., Hutton, J., Roe, D., Vira, B., Wolmer, W. (2004) Biodiversity conservation and the eradication of poverty. Science 306, 1146-1149.

AES, (2012) http://www.aeschanguinola.com/aes_changuinola.asp.

ANAM, (2006) Indicadores Ambientales de la República de Panamá. Autoridad Nacional del Ambiente, Panamá, República de Panamá.

ANAM, (2008) Infraestructura en Áreas Protegidas

Período 2007 – 2008. Autoridad Nacional del Ambiente, Dirección Nacional de Áreas Protegidas y Vida Silvestre, Panamá, República de Panamá.

ANAM, (2011) Compendio de estadisticas 2011. (Cuadro 20-8. Guardaparques por Área Protegida : enero-junio 2011). Autoridad Nacional del Ambiente, Panamá, Republica de Panamá.

ANAM/CBMAP, (2006) Plan de Manejo Actualizado: Bosque Protector de Palo Seco. Autoridad Nacional del Ambiente y Corredor Biologico Mesoamericano del Atlantico Panameno, Panama, Republica de Panama.

ANAM/ITTO, (2003) Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. Autoridad Nacional del Ambiente, Panama, Republica de Panama, p. 107 pp.

Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G.A., Robalino, J.A. (2008) Measuring the effectiveness of protected area networks in reducing deforestation. Proceedings of the National Academy of Sciences of the United States of America 105, 16089-16094.

Angelsen, A. (2010) Policies for reduced deforestation and their impact on agricultural production. Proceedings of the National Academy of Sciences of the United States of America 107, 19639-19644.

Asamblea Legislativa, (7 de marzo 1997) Ley N° 10 "Por la cual se crea la Comarca Ngóbe-Buglé y se toman otras medidas", Panamá, República de Panamá.

Balmford, A., Whitten, T. (2003) Who should pay for tropical conservation, and how could the costs be met? Oryx 37, 238-250.

Barrett, C.B. (2010) Measuring Food Insecurity. Science 327, 825-828.

Berkes , F., Colding, J., Folke, C., (2003) Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, UK.

Bort, J.R., Young, P.D. (1985) Economic and Political Adaptation to National-Development among the Guaymi. Anthropological Quarterly 58, 1-12.

Brockington, D., Igoe, J., Schmidt-Soltau, K. (2006) Conservation, human rights, and poverty reduction. Conservation Biology 20, 250-252.

Brown, D., Seymour, F., Peskett, L., (2008) How do we achieve REDD co-benefits and avoid doing harm?, in: Angelsen, A. (Ed.), Moving Ahead with REDD: Issues, Options and Implications. CIFOR, Bogor, Indonesia, p. 156p.

Cernea, M., Schmidt-Soltau, K. (2006) Poverty Risks and National Parks: Policy Issues in Conservation and Resettlement. World Development 34, 1808–1830.

Contraloría, (2011) Censo Nacional de Población y Vivienda de 2010. Dirección de Estadística y Censo, Contraloria Nacional de la República de Panamá, Panamá.

Coomes, O.T., Takasaki, Y., Rhemtulla, J.M. (2011) Land-use poverty traps identified in shifting cultivation systems shape long-term tropical forest cover. Proceedings of the National Academy of Sciences of the United States of America 108, 13925-13930.

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I., Kasischke, E. (2004) Lowland Forest Loss in Protected Areas of Indonesian Borneo. Science 303, 1000-1003.

DeFries, R., Hansen, A., Newton, A.C., Hansen, M.C. (2005) Increasing isolation of protected areas in tropical forests over the past twenty years. Ecological Applications 15, 19-26.

DeFries, R., Hansen, H., Turner, B.L., Reid, R., Liu, J. (2007) Land use change around protected areas: management to balance human needs and ecological function. Ecological Applications 17, 974-988.

Evans, K., De Jong, W., Cronkleton, P., Sheil, D., Lynam, T., Kusumanto, T., Pierce Colfer, C.J., (2006) Guide to Participatory Tools for Forest Communities. Center for International Forestry Research (CIFOR), Bogor, Indonesia, p. 37.

Ferraro, P.J. (2002) The local costs of establishing protected areas in low-income nations: Ranomafana National Park, Madagascar. Ecological Economics 43, 261-275.

Ferraro, P.J., Hanauer, M.M., Sims, K.R.E. (2011) Conditions associated with protected area success in conservation and poverty reduction. Proceedings of the National Academy of Sciences of the United States of America 108, 13913-13918.

Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B., Bengtsson, J., Berkes, F., Colding, J., Danell, K., Falkenmark, M., Gordon, L., Kasperson, R., Kautsky, N., Kinzig, A., Levin, S., Maler, K., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockstrom, J., Savenije, H., Svedin, U., (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations, Scientific Background Paper on Resilience for the Process of the World Summit on Sustainable Development on Behalf of the Environmental Advisory Council to the Swedish Government.

Fundación del Consejo General de la Abogacía Española, (2011) "Impunidad e Indefensión: caso Chan 75 (Bocas Del Toro, Panamá)", Caso 12.717 iniciado ante la Comisión Interamericana de Derechos Humanos: análysis de la situación de las comunidades indígenas Ngöbe-Buglé afectadas por la construcción de la presa Chan 75, pp. 1-72.

Gaceta Oficial, (1 Junio 2006) Decreto Ejecutivo N°71 "Por el cual se modifica el artículo 3 del Decreto 25 de 28 de septiembre de 1983 [...]". Ministerio de Economía y Finanzas, Panamá, República de Panamá.

Gaceta Oficial, (28 de septiembre de 1983) Decreto Ejecutivo N° 25 "Por el cual se declara y se describe el Bosque Protector de Palo Seco en los Distritos de Chiriquí Grande y Changuinola, Provincia de Bocas del Toro". República de Panamá.

GEF, (2005) Financial Sustainability for National Systems of Protected Areas: Panama Country Support Plan. Autoridad Nacional del Ambiente, Panamá, República de Panamá.

Geist, H.J., Lambin, E.F. (2002) Proximate causes and underlying driving forces of tropical deforestation. Bioscience 52, 143-150.

Green, R.E., Cornell, S.J., Scharlemann, J.r.P.W., Balmford, A. (2005) Farming and the Fate of Wild Nature. Science 307, 550-555.

IUCN, (1994) Guidelines for Protected Areas Management Categories, CNPPA with the assistance of WCMC. The World Conservation Union, Gland, Switzerland and Cambridge, UK, p. 261

Joppa, L.N., Loarie, S.R., Pimm, S.L. (2008) On the protection of "protected areas". Proceedings of the National Academy of Sciences of the United States of America 105, 6673-6678.

Kumar, S. (2002) Methods for Community Participation: A Complete Guide for Practitioners. Practical Action Publishing, Warwickshire, UK.

Mascia, M., Pailler, S. (2011) Protected area downgrading, downsizing, and degazettement (PADDD) and its conservation implications. Conservation letters 4, 9-20.

MIDES, (2012) Programa Red de Oportunidades, Available online at http://www.mides.gob.pa/?page_id=2927. Ministerio de Desarrollo Social, Panamá, República de Panamá.

Mosaquites, J.N., (2008) Estudio de la comunidad indígena Ngäbe de Valle de Riscó ubicada en el Bosque Protector de Palo Seco: ¿Oportunidad para el manejo y conservación, o causa para el deterioro irreversible de los recursos naturales?, Escuela de Ciencias Agrarias Programa Regional de Maestría en Desarrollo Rural. Universidad Nacional Heredia, Costa Rica, p. 244.

Murphy, D., (2011) Safeguards and Multiple Benefits in a REDD+ Mechanism. International Institute for Sustainable Development (IISD), Winnipeg, Canada.

Naughton-Treves, L., Alix-Garcia, J., Chapman, C.A. (2011) Lessons about parks and poverty from a decade of forest loss and economic growth around Kibale National Park, Uganda. Proceedings of the National Academy of Sciences of the United States of America 108, 13919-13924.

Naughton-Treves, L., Holland, M.B., Brandon, K. (2005) The role of protected areas in conserving biodiversity and sustaining local livelihoods. Annual Review of Environment and Resources 30, 219-252.

Nelson, A., Chomitz, K.M. (2011) Effectiveness of Strict vs. Multiple Use Protected Areas in Reducing Tropical Forest Fires: A Global Analysis Using Matching Methods. Plos One 6.

Nepstad, D., Schwartzman, S., Bamberger, B., Santilli, M., Ray, D., Schlesinger, P., Lefebvre, P., Alencar, A., Prinz, E., Fiske, G., Rolla, A. (2006) Inhibition of

Amazon deforestation and fire by parks and indigenous lands. Conservation Biology 20, 65-73.

Oestreicher, J.S., Benessaiah, K., Ruiz-Jaen, M.C., Sloan, S., Turner, K., Pelletier, J., Guay, B., Clark, K.E., Roche, D.G., Meiners, M., Potvin, C. (2009) Avoiding deforestation in Panamanian protected areas: An analysis of protection effectiveness and implications for reducing emissions from deforestation and forest degradation. Global Environmental Change 19, 279-291.

Ostrom, E. (1990) Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press.

Ostrom, E., Nagendra, H. (2006) Insights on linking forests, trees, and people from the air, on the ground, and in the laboratory. Proceedings of the National Academy of Sciences of the United States of America 103, 19224-19231.

Pirard, R., Belna, K. (2012) Agriculture and Deforestation: Is REDD+ Rooted In Evidence? Forest Policy and Economics *in press*.

Ricketts, T.H., Soares-Filho, B., da Fonseca, G.A.B., Nepstad, D., Pfaff, A., Petsonk, A., Anderson, A., Boucher, D., Cattaneo, A., Conte, M., Creighton, K., Linden, L., Maretti, C., Moutinho, P., Ullman, R., Victurine, R. (2010) Indigenous lands, protected areas, and slowing climate change. PLoS Biology 8, e1000331.

Scharlemann, J.P.W., Kapos, V., Campbell, A., Lysenko, I., Burgess, N.D., Hansen, M.C., Gibbs, H.K., Dickson, B., Miles, L. (2010) Securing tropical forest carbon: the contribution of protected areas to REDD. Oryx 44, 352-357.

Smith, D.A. (2005) Garden game: Shifting cultivation, indigenous hunting and wildlife ecology in western Panama. Human Ecology 33, 505-537.

Sodhi, N.S., Lee, T.M., Sekercioglu, C.H., Webb, E.L., Prawiradilaga, D.M., Lohman, D.J., Pierce, N.E., Diesmos, A.C., Rao, M., Ehrlich, P.R. (2010) Local people value environmental services provided by forested parks. Biodiversity and Conservation 19, 1175-1188.

Terborgh, J., Peres, C., (2002) The problem of people in parks, in: Rao, M. (Ed.), Making parks work: Strategies for preserving tropical nature. Island Press, Washington, D.C., USA, pp. 307-319.

UNFCCC (2010a) Guidance and safeguards for policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. Annex I to the Cancun Agreement.

UNFCCC, (2010b) Outcome of the work of the Ad Hoc Working Group on long-term Cooperative Action under the Convention, Draft decision [-/CP.16]. United Framework Convention on Climate Change.

Upton, C., Ladle, R., Hulme, D., Jiang, T., Brockington, D., Adams, W.M. (2008) Are poverty and protected area establishment linked at a national scale? Oryx 42, 19-25.

West, P., Igoe, J., Brockington, D. (2006) Parks and peoples: The social impact of protected areas. Annual Review of Anthropology 35, 251-277.

Wickstrom, S. (2003) The politics of development in indigenous Panama. Latin American Perspectives 30, 43-68.

Wittemyer, G., Elsen, P., Bean, W.T., O. Burton, C.A., Brashares, J.S. (2008) Accelerated Human Population Growth at Protected Area Edges. Science 321, 123-126.

Wollenberg, E., Edmunds, D., Buck, L., (2000a) Anticipating Change: Scenarios as a Tool for Adaptive Forest Management. Center for International Forestry Research, Bogor, Indonesia, p. 38.

Wollenberg, E., Edmunds, D., Buck, L. (2000b) Using scenarios to make decisions about the future: anticipatory learning for the adaptive co-management of community forests. Landscape and Urban Planning 47, 65-77.

Young, P.D. (1971) Ngawbe: Tradition and Change among the Western Guaymí of Panama. University of Illinois Press, Urbana, USA.

Young, P.D., Bort, J., (1999) Ngobe Responses to Globalization in Panama., in: Locker, W.M. (Ed.), Globalization and Rural Poor in Latin America. Lynne Rienner Publishers, Boulder, CO, pp. pp. 111-136.

Young, P.D., Bort, J.R., (1995) Ngawbe, in: Levinson, D. (Ed.), Encyclopedia of World Cultures. G. K. Hall, Boston, pp. 194-199.

TABLES AND FIGURES

Table 1. Households Characteristics and land distribution amongst the interviewees (n=45).

	Mean	**Standard Deviation**	**Range**
Household size	8.4	5.1	(2-20)
Children per household (<15 years)	4.8	3.4	(0-16)
Total landholdings (in ha)	32.0	41.7	(0-210)
Forest (in ha)	20.7	35.0	(0-204)
Young fallow (in ha)	4.3	6.9	(0-35)
Old fallow (in ha)	3.6	5.4	(0-25)
Annual Crop (in ha)	0.1	0.4	(0-2)
Pasture (in ha)	1.0	2.4	(0-11)
Fruit plants or trees (in ha)	2.0	2.0	(0-8)

Table 2. Percentage of households involved in the following main economic activities (n=45).

Economic activities	Households involved in the activity (in %)	Mean (SD)
Subsistence agriculture	100	
Cash crop (*Culantro*)	56	
Number of plots		*2.17 (1.15)*
Cattle ranching	29	
Number of cattle		*3.46 (3.31)*
Coffee harvesting	29	
Sale of production surplus	44	
Governmental assistance (Red de Oportunidad)	91	
Handcrafting sold	4	
Land renting	13	
Lumber for sold	9	
Universal (education) grant	58	
Wage labour	20	
Other income*	18	

* This category includes incomes from holding a store in the village or from sawing lumber with chainsaw.

Table 3. Agricultural practices and preferences amongst interviewees (n=45)

	Occurrence amongst households (in %)	Mean (SD)
Practices		
Permanent cultivation (No fallow)	22.2	
Household that cleared forest or fallow last year	44.4	
Cleared area		0.9 (0.6)
Household using agriculture-fallow cycle		
Cultivation length		1.7 (1.5)
Fallow length		3.8 (2.6)
Notice change in production overtime	64.4	
Perceive they need to clear more land	75.6	
Practice Clearing	86.7	
Preferences		
Forest land for planting	28.9	
Fallow land for planting	60.0	
Choice of land affected by slope	33.3	
Choice of land affected by distance	60.0	
Use of natural fertilizer	13.3	
Use of chimical fertilizer	20.0	

Table 4. Factors to increase deforestation (n=50)

Factors in order of importance (in parenthesis- number of time mentioned)
Population growth (35)
Cattle ranching (10)
Cattle ranching and population growth (3)
Campesinos (3)
Immigration to the area (3), of Ngäbes (2 out of 3)
Lack of education and institutional support (3)
Lack of food (2)
Timber sell (2)
Hydroelectric project (2)
Corn production (1)
Culantro production (1)
Institutional weakness (1)
New land needed by community member (1)
Personal decision of landowners (1)

Table 5. Positive aspects of living in the protected area according to household participants (n=45).

Positive aspects - Benefits (n=45)	Frequency mentionned	%
Clean water and river access	30	66.7
Building material for houses (Timber, *Penca*, *Chonta*, *Bejuco*)	17	37.8
Firewood	15	33.3
Cool and clean environment (for health)	13	28.9
Wild animals for consumption	12	26.7
Forest/nature/scenic area/wild animals	12	26.7
Access to land/ Farm nearby	9	20.0
Road access	6	13.3
Community development project	5	11.1
Law of protected area (protect resources)	3	6.7
Employment opportunities	3	6.7
Kalalu (edible fern)	2	4.4
Food production	2	4.4
School	2	4.4
No benefits	2	4.4
Medicinal plants	1	2.2
Tranquility	1	2.2

Table 6. Negative aspects of living in the protected area according to household participants (n=45).

Negative aspects - Restriction (n=45)	Frequency mentionned	%
Forest clearing for agriculture (work)	42	93.3
Hunting for food	26	57.8
Timber harvesting and sale	25	55.6
Burning (*quema)*	18	40.0
Cattle ranching	11	24.4
Hunting with a dog	4	8.9
Use chemicals for fishing	3	6.7
Fumigation/pesticides	3	6.7
No negative aspect	3	6.7
Cultivate	1	2.2
Fishing	1	2.2
Firewood	1	2.2

Table 7. Alternatives proposed to maintain forest in the area and risks associated as compiles from interviews (n=50).

Type of proposition	Alternatives/activities proposed	Potential Risks
Agricultural production	- Access road to the village (send produce to market) - Production alternatives for food and market (including coffee, *ají*, cacao (in agroforestry system)) - Timber, firewood and fruit tree plantations - Chicken, eggs, pork, lamb or/and fish production	- Road: increased migration to the area or/and illegal logging - Adoption of cash crops that stimulates forest conversion
Employment	- Tourism project - Self-management of handcrafting-women - Forest rangers	- Financial benefits to a minority of people with possibly small net effect on forest cover change
Payment for Environmental Services	**Direct payment**: - Compensation for conserving forest on their land (payment per ha of forest or equal for all) - Monetary incentive coupled with education and technical assistance	- Investment in activities promoting forest cover change ("If I had money, I would buy cattle") - Paternalism and dependence - Difficult process to clarify on untitled land (land is often informally given –intergeneration conflicts) - "Money is easily spent/Money might not even reach the community" - Food security "we will produce less food" - Money given individually may generate conflicts
	Funds: - Finance projects of agricultural production and employment (see above) - Strengthening of the environmental institution (ANAM) - Fortifying local organization (social capital) - Social programs with environmental education	- Overtaken by local elite, limited benefits to the community - "Money is politically managed" and does not reach the community
Capacity-building and Education	- Grants for students/Access to education - Technical assistance for production - Capacity-building - Environmental education	
General measures	- Creation of a specialized institution to attend to poverty in rural areas	

Table 8. Criteria and conditions for participating in a project to maintain forest

General involvement criteria	- Be voluntary - Promote self-management - Not prevent use of the forest/Not require the land to be given, ceded or to limit access to the land - Have continuity overtime and provide regularly - Provide incentive for both men and women - Let us work [clear forest] for subsistence/ Allow to cultivate for the family's well-being - Not be permanent to prevent restricting our children's opportunity (Involvement has to have time limit)
Decision Process	- Take into account the community's opinion/Be consensual throughout the community/Be agreed to by the community - Build trust/Not cheat the community - Take the time necessary to develop the project - Inform the community on advantages and disadvantages/Be clear on what will be done and the benefits - Obtain information on the landholding/Detect unequal land distribution that would create more inequality - Be discussed by community with the institution managing the Palo Seco Forest Reserve
Expectations towards Benefits and subsistence	- Bring benefits in exchange for work (something to maintain the family (mainly food) and benefits to the community) - Be sufficient to benefit the whole family (How to conserve forest if I have to sustain the family?) - Provide cash incentive (with cash it is possible to eat and conserve forest) - Not be exclusively monetary/ Include support with equipment and materials - Allow for clearing of forest for subsistence agriculture if necessary - Account for who has conserved forests and who has cleared in the past - Generate resources for the community - Provide security on what we will depend on - Promote improvements for families and support to the community - Offer more than what the community has received to date - Promote capacity-building to help produce more and better/ Teach us how cultivate land and protect natural resources
Organization of work	- Involve an organization of work (including benefits) that is: 1) individual work (Majority of interviewees), 2) in group and individual work or 3) in group. Individual work is preferred to avoid conflicts. Work developed in groups and in a united way is to share equally. - Be within an organized community framework - Be at the responsibility of the most liable and experienced people in the community

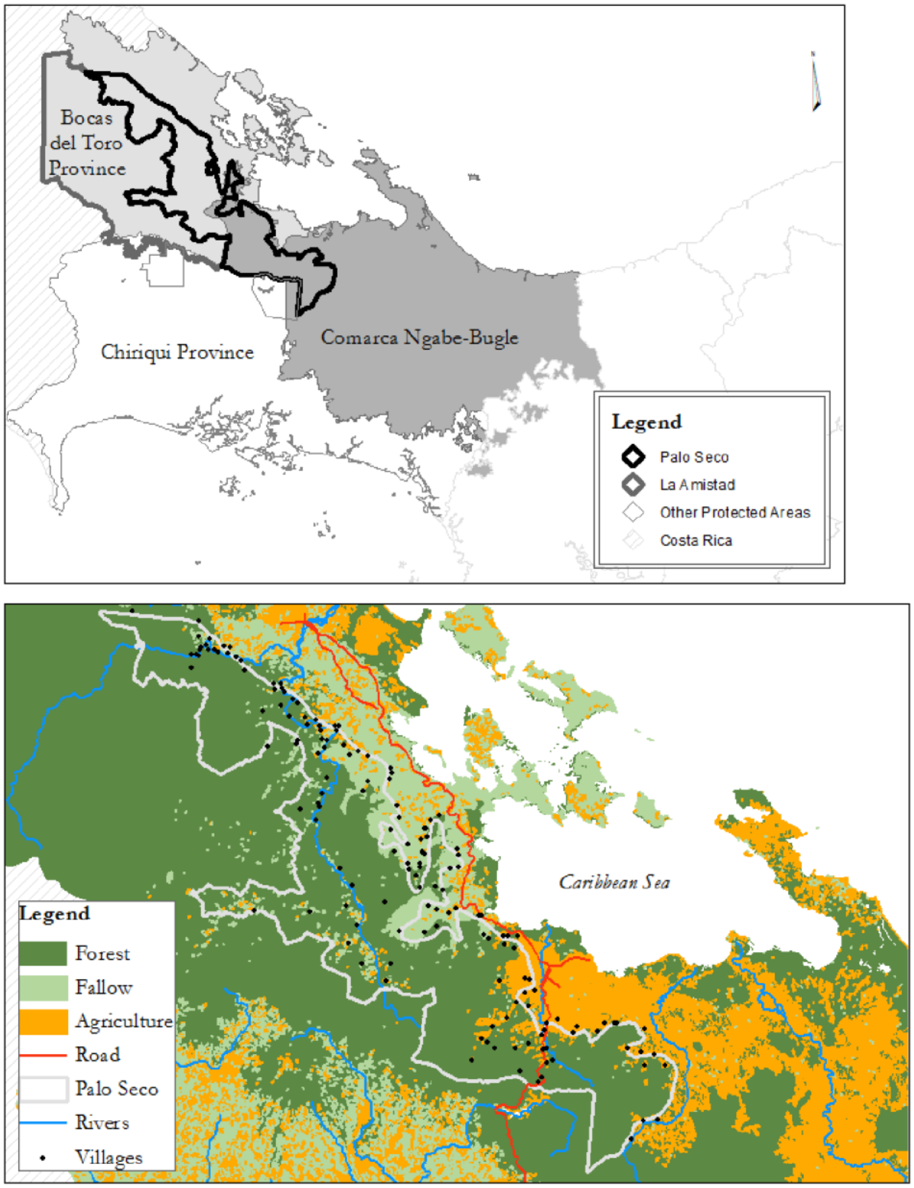
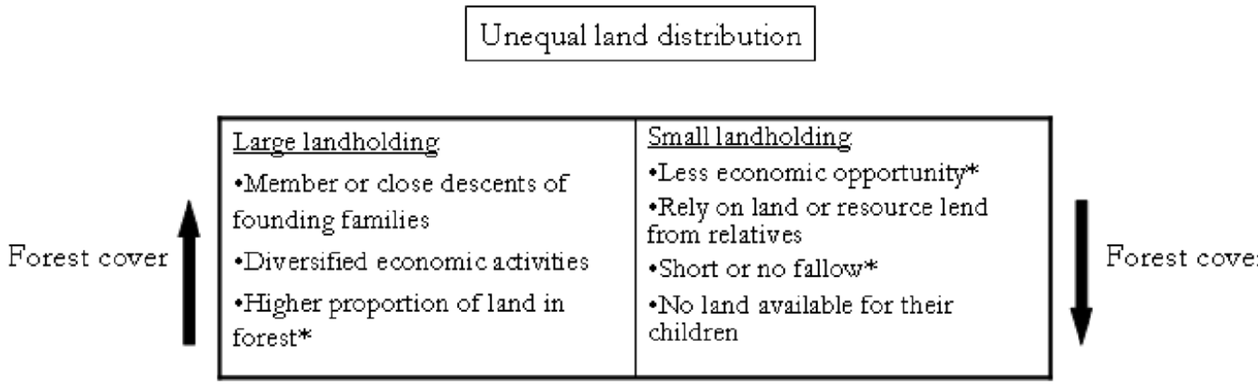


Figure 1. Map of the region top panel and land-cover map with Palo Seco boundary.



* Indicate where we have found significant difference or relationship. Early decision about land use also determines the proportion of forest cover and future economic opportunities (See Coomes *et al.* (2011)).

Figure 2. Implications of farm size on forest cover and economic opportunities.

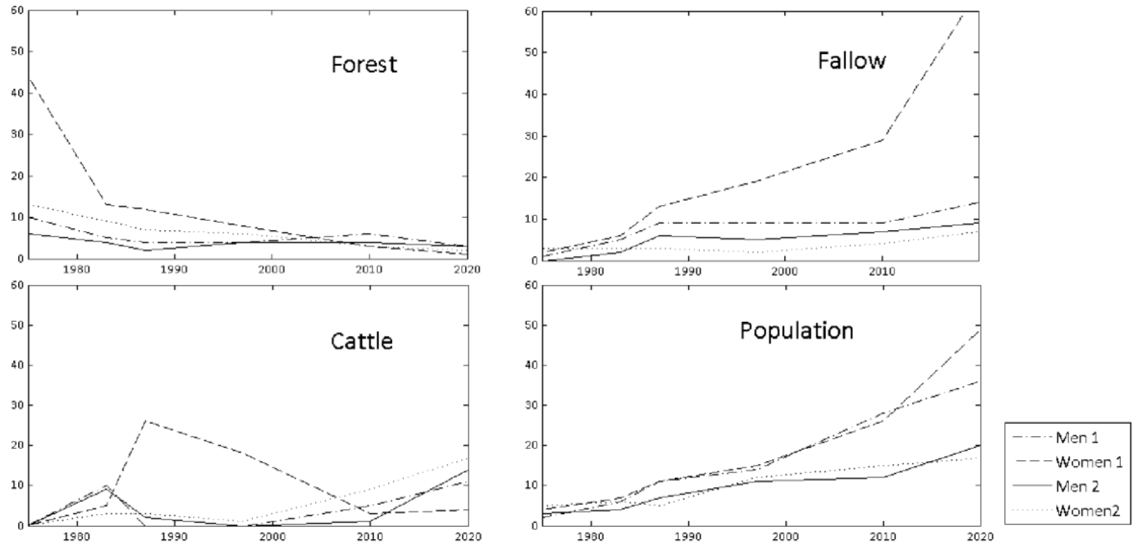


Figure 3. Trend analysis of resources carried out with four focus group (two with women; two with men) from the village founding until 10 years into the future.

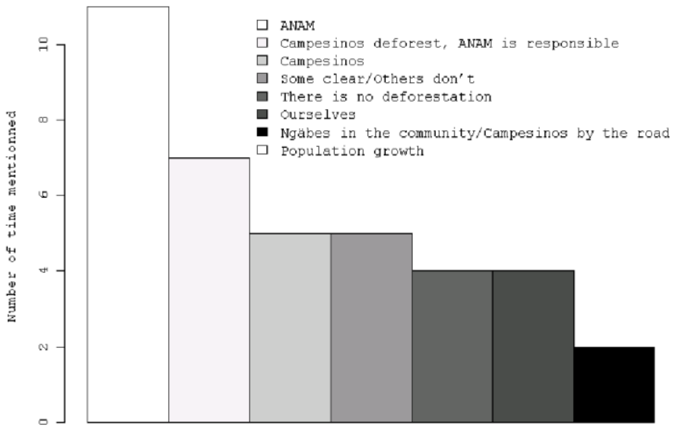


Figure 4. Responsible for deforestation according to participants (n=50).

Final summary and conclusions

Deforestation and forest degradation are posing important challenges to the sustainability of ecosystem services of global value (Foley et al., 2005). Recently, there has been much enthusiasm for the elaboration of a REDD+ mechanism to account for the role of forests in climate mitigation. The two fundamental research axes for the creation of this mechanism are: 1) the methodological and technical challenge, involving issues necessary to establish a performance-based approach and 2) the subject of forest governance, moving towards “slowing, halting, and reversing the loss and degradation of forests in developing countries” (UNFCCC, 2010).

In this thesis, we have used Panama as a case study to look at different aspects of land-cover change CO2 flux. The results of this work however, reach beyond the borders of Panama and are relevant for other tropical developing countries. A technical report produced by the UNFCCC indicates that the majority of non-annex I countries have a limited capacity to provide complete and accurate estimates of GHG emissions and removals from forests (UNFCCC 2009). Herold (2009) in an assessment of national forest monitoring capabilities in tropical non-Annex I countries has shown that only 3 out of 99 countries have a “very high” capacity to monitor both forest area change and forest carbon inventory, namely India, China, and Mexico. Compared to other tropical developing countries, Panama is ranked as having an “advanced” staged of completeness in GHG inventory, a “good” forest area change monitoring capacity and a “limited” forest inventory capacity (Herold, 2009). It is therefore important to see that several countries have currently much less capability to monitor their forests for REDD+ than Panama, and thus the uncertainty levels found through this case study could potentially be higher in those countries while they could be lower or comparable to the uncertainty levels found in more advanced developing countries.

Accounting for uncertainty in forest-related flux is especially important in the context of possible REDD+ tradable emission reductions. Gupta et al. (2003) have pointed out that under the Kyoto Protocol compliance mechanism, the emission reductions are as high as the uncertainty around them and thus, the probability of compliance is low. In effect, if uncertain emission reductions from REDD+ are used to offset well-known emissions from fossil fuel combustion, there is a high probability that no benefits will entail for the climate. In Durban, Parties to the UNFCCC agreed for the first time on a general and broad framework for the financing of REDD+. Decision 1/CP17, in its articles 65-67, first indicates that “result-based finance” for REDD+ “may come from public, private, bilateral and multilateral […] sources”. It follows by indicating that “appropriate new market-based approaches could be developed” and that these new approaches would have to respect environmental integrity and REDD+ implementation safeguards. As the ultimate objective of the Convention is to stabilize the GHG concentrations in the atmosphere, it is relevant to wonder if REDD+ uncertainty might not jeopardize the integrity of the future climate regime. Our work on the uncertainties surrounding estimates of emissions from the land use sector is relevant to the current international debate around REDD+ financing where some countries oppose the use of the REDD+ unit being traded on a compliance market.

In **Chapter 1** and **2** of this thesis, I measured the level and the significance of uncertainty in carbon dioxide (CO_2) emissions from LUCC in Panama and showed that they could be as high as ±43.5%. Combining modeling and uncertainty propagation on data available in Panama for measuring forest-related emissions, I highlighted the importance of acquiring appropriate data, and identified where the efforts in collecting additional information should be focused to maximize the reduction in uncertainty. The sources of uncertainty identified by this research are of great relevance for the tropics. An emerging priority is the improvement of forest carbon density estimations. The approach that I proposed is likely to increase the robustness and credibility of REDD+ on the long term and improve the ability to detect emission reductions. In **Chapter 3**, I demonstrated that processes associated to previously ignored land-use dynamics can be monitored adequately with accessible medium-resolution imagery. By doing so I addressed one of the main technical challenges for REDD+ monitoring that related to forest degradation and for which the Intergovernmental Panel on Climate Change (IPCC) does not have a readily available methodology. A recently published paper used a similar approach of a time series of remote sensing images to predict aboveground live biomass over the Northern Pacific forest (Powell et al., 2010) thereby lending some added credibility to my efforts. As a next step, I believe that the methodological approach developed in Chapter 3 should be tested on a larger scale than was possible in the framework of this thesis.

While these three chapters have contributed to the first research axis on methodological issues, **Chapter 4** focuses on forest governance issues relevant to the second research axis, by exploring the local perceptions of people living in a protected area to allow for an informed REDD+ national strategy. This second axis adds an interdisciplinary aspect to this Ph.D. thesis. The interest in the perceptions of forest dwellers living inside a national protected area stems from the assumption that lessons from various demonstration activities implemented in different countries and analyzed in the context of REDD+ will help generate guidelines for renewed forest governance in the context of climate mitigation. A main constraint identified in **Chapter 4** is the importance of food security in forested areas, suggesting that it requires attention when designing policies to reduce deforestation (Angelsen, 2010). Currently, emphasis is put on agriculture intensification despite uncertain consequences on forest cover (Pirard and Belna, 2012). However, my results point out the need to incorporate an understanding of subsistence agriculture in the development of policy. For example, the appreciation and valorization of agroforestry for forest conservation and food security in Palo Seco Forest Reserve would need to be further studied to evaluate current land allocation as well as actual and potential livelihood and carbon benefits. At this point, there is no information about the contribution of the current diversified agroforestry systems used by indigenous people in the protected area. This could be done by conjugating hyperspectral satellite imagery to detect the presence of the main fruit trees using their spectral signature and by conducting household surveys to determine the income and food produced, as well as potential production improvements.

In conclusion, this research suggests that further important research advances are still needed or at least that certain proposed approaches should be tested before REDD+ performance-based payments can satisfy the level of accuracy and credibility essential for a market-based approach. This work also emphasizes the challenges in forest governance if REDD+ safeguards are to be implemented. The conservativeness approach has been proposed to deal with uncertainty in emission reductions estimates resulting from actions taken to reduce emissions from deforestation (GOFC-GOLD, 2010; Grassi et al., 2008).

As an alternative, the matrix approach proposed by (Bucki et al., 2012) to enable fast implementation of REDD+ could offer a pragmatic solution of assessing the performance of the five REDD+ activities by prioritizing better area measurements from remote sensing while allowing for the use of even Tier 1 default emission factors until better alternatives become available. Using this simplified MRV scheme could provide incentives to developing countries by rewarding early actions and enabling a gradual build-up of capacities, instead of delaying climate mitigation actions for technical issues. As such, a promising avenue of future research should begin, aiming at evaluating the economic tradeoffs between, on one hand, investing large effort and hence resources, in monitoring emission reductions and, on the other hand, implementing REDD+ activities under current capacities with all the associated benefits. It is my opinion that donor and REDD+ countries would benefit from clear guidance on the costs of improving accuracy as a way to guide resource allocation.

REFERENCES

Angelsen, A. (2010) Policies for reduced deforestation and their impact on agricultural production. Proceedings of the National Academy of Sciences of the United States of America 107, 19639-19644.

Bucki, M., Cuypers, D., Mayaux, P., Achard, F., Estreguil, C., Grassi, G. (2012) The matrix approach: a pragmatic solution for rapid REDD+ implementation. Environmental Research Letters *submitted*.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. (2005) Global consequences of land use. Science 309, 570-574.

GOFC-GOLD, (2010) A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation, GOFC-GOLD Report version COP16-1. GOFC-GOLD Project Office, Natural Resources Canada, Alberta, Canada.

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D. (2008) Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates. Environmental Research Letters 3, 035005.

Gupta, J., Olsthoorn, X., Rotenberg, E. (2003) The role of scientific uncertainty in compliance with the Kyoto Protocol to the Climate Change Convention. Environmental Science & Policy 6, 475-486.

Herold, M., (2009) An assessment of national forest monitoring capabilities in tropical non-Annex I countries: Recommendations for capacity building. Friedrich Schiller University Jena and GOFC-GOLD Land Cover Project Office, p. 61.

Pirard, R., Belna, K. (2012) Agriculture and Deforestation: Is REDD+ Rooted In Evidence? Forest Policy and Economics *in press*.

Powell, S.L., Cohen, W.B., Healey, S.P., Kennedy, R.E., Moisen, G.G., Pierce, K.B., Ohmann, J.L. (2010) Quantification of Live Aboveground Forest Biomass Dynamics with Landsat

Time-Series and Field Inventory Data: A Comparison of Empirical Modeling Approaches. Remote Sensing of Environment 114, 1053-1068.

UNFCCC, (2009) Cost of implementing methodologies and monitoring systems relating to estimates of emissions from deforestation and forest degradation, the assessment of carbon stocks and greenhouse gas emissions from changes in forest cover, and the enhancement of forest carbon stocks., FCCC/TP/2009/1.

UNFCCC, (2010) The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention, Decision 1/CP.16. United Framework Convention on Climate Change.

UNFCCC, (2011) Establishment of an Ad Hoc Working Group on the Durban Platform for Enhanced Action, Decision 1/CP.17. United Nations Framework Convention on Climate Change.

ANNEX

Model Description

Here we provide the details on the land-cover transition model and the book-keeping carbon cycle model. The same model structure was repeated for the eight life zones with there respective parameters that can be found in [S1] and [S2].

A1. Land-cover transition model

Let $D(t)$, t = 1990, 1991, …, 2030 be the deforestation rates at time 't' in ha yr^{-1}.

Let $A_F(t,\tau), \begin{matrix} t=1990,1991,\ldots,2030 \\ \tau=1,2,\ldots,t-1990+1 \end{matrix}$ be the area of mature forest (ha yr^{-1}) at time 't', age-cohort 'τ',

let $A_{SF}(t,\tau), \begin{matrix} t=1990,1991,\ldots,2030 \\ \tau=1,2,\ldots,t-1990+1 \end{matrix}$ be the area of secondary forest (ha yr^{-1}) at time 't', age-cohort 'τ',

let $A_{FA}(t,\tau), \begin{matrix} t=1990,1991,\ldots,2030 \\ \tau=1,2,\ldots,t-1990+1 \end{matrix}$ be the area of fallow (ha yr^{-1}) at time 't', age-cohort 'τ',

let $A_{AG}(t,\tau), \begin{matrix} t=1990,1991,\ldots,2030 \\ \tau=1,2,\ldots,t-1990+1 \end{matrix}$ be the area of agriculture (ha yr^{-1}) at time 't', age-cohort 'τ', and

let $A_O(t,\tau), \begin{matrix} t=1990,1991,\ldots,2030 \\ \tau=1,2,\ldots,t-1990+1 \end{matrix}$ be the area of other land (ha yr^{-1}) at time 't', age-cohort 'τ'.

A first-order Markov model of transition probabilities between land-cover classes can be specified as follows:

$$\begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t,\tau} = \begin{bmatrix} \alpha_{F,F} & \alpha_{SF,F} & \alpha_{FA,F} & \alpha_{AG,F} & \alpha_{O,F} \\ \alpha_{F,SF} & \alpha_{SF,SF} & \alpha_{FA,SF} & \alpha_{AG,SF} & \alpha_{O,SF} \\ \alpha_{F,FA} & \alpha_{SF,FA} & \alpha_{FA,FA} & \alpha_{AG,FA} & \alpha_{O,FA} \\ \alpha_{F,AG} & \alpha_{SF,AG} & \alpha_{FA,AG} & \alpha_{AG,AG} & \alpha_{O,AG} \\ \alpha_{F,O} & \alpha_{SF,O} & \alpha_{FA,O} & \alpha_{AG,O} & \alpha_{O,O} \end{bmatrix} \begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t-1,\tau-1}$$

, where

the matrix α contains the land-cover transition probabilities. The transition matrices can be found in S2.

However, a transition from one land-cover class to another should reset the cohort age to 1, and therefore the above form of the equation is applied as follows:

First, the deforested land every year is partitioned into the 1-yr age classes as follows:

$A_F(t, 1) = D(\mathrm{t}) \times K_F$

$A_{SF}(t, 1) = D(\mathrm{t}) \times K_{SF}$

$A_{FA}(t, 1) = D(\mathrm{t}) \times K_{FA}$

$A_{AG}(t, 1) = D(\mathrm{t}) \times K_{AG}$

$A_O(t, 1) = D(\mathrm{t}) \times K_O$,

Where K is the fraction of deforested land that goes into mature forest, secondary forest, fallow, agriculture or other land cover (S1) and where K_F is equal to zero.

Next, to the 1-yr age cohorts, we add the area that results from the transition from other land-cover classes:

$$\begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t,1} = \begin{bmatrix} K_F D(t) \\ K_{SF} D(t) \\ K_{FA} D(t) \\ K_{AG} D(t) \\ K_O D(t) \end{bmatrix} + \begin{bmatrix} 0 & \alpha_{SF,F} & \alpha_{FA,F} & \alpha_{AG,F} & \alpha_{O,F} \\ 0 & 0 & \alpha_{FA,SF} & \alpha_{AG,SF} & \alpha_{O,SF} \\ 0 & \alpha_{SF,FA} & 0 & \alpha_{AG,FA} & \alpha_{O,FA} \\ 0 & \alpha_{SF,AG} & \alpha_{FA,AG} & 0 & \alpha_{O,AG} \\ 0 & \alpha_{SF,O} & \alpha_{FA,O} & \alpha_{AG,O} & 0 \end{bmatrix} \begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t-1,\tau-1} .$$

Finally, for age cohorts older than 1 year, we estimate the within-class transition of land-cover classes:

$$\begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t,\tau} = \begin{bmatrix} \alpha_{F,F} & 0 & 0 & 0 & 0 \\ 0 & \alpha_{SF,SF} & 0 & 0 & 0 \\ 0 & 0 & \alpha_{FA,FA} & 0 & 0 \\ 0 & 0 & 0 & \alpha_{AG,AG} & 0 \\ 0 & 0 & 0 & 0 & \alpha_{O,O} \end{bmatrix} \begin{bmatrix} A_F \\ A_{SF} \\ A_{FA} \\ A_{AG} \\ A_O \end{bmatrix}^{t-1,\tau-1} \text{, for } \tau = 2, 3,,,, t.$$

The initial conditions for this model are the 1990 land cover conditions which can be found in S1 per life zone under A_F, A_{SF}, A_{FA}, A_{AG}, and A_O. We kept track of existing secondary forest in 1990 by averaging all their age classes and by specifying an average biomass value, as the age of this existing secondary forest was unknown.

From the results of this model, we can also calculate the annual rate of re-clearing of secondary vegetation as:

$$A_{SF,clear}(t,\tau) = A_{SF}(t-1,\tau-1)(\alpha_{SF,FA} + \alpha_{SF,AG} + \alpha_{SF,O}),$$

This re-clearing of the secondary vegetation can be divided into two sub-categories: the clearing of secondary forest that was already present in 1990 $I_{SF,clear}$ (initial conditions) and the clearing of secondary forest newly created after 1990 $S_{SF,clear}$, are given by :

1) $I_{SF,clear}(t) = diag\,(A_{SF,clear}(t,\tau))$, and

2) $S_{SF,clear}(t,\tau) = A_{SF,clear}(t,\tau) - diag(I_{SF,clear}(t))$, where $diag(I_{SF,clear}(t))$ is the diagonal matrix with the vector $I_{SF,clear}$ as the main diagonal.

The annual re-growth of secondary vegetation can be calculated as:

1) For the secondary forest already present in 1990:

$$A_{SF,initial}(t) = diag(A_{SF}(t,\tau))$$

2) Secondary forest created throughout the simulation:

$A_{SF,new}(t,\tau) = A_{SF}(t,\tau) - diag(diag(A_{SF}(t,\tau)))$, where $A_{SF,new}(t,\tau)$ is the same matrix as $A_{SF}(t,\tau)$ without the elements in the diagonal.

The annual rate of re-clearing of fallow land correspond to:

$$A_{FA,clear}(t,\tau) = A_{FA}(t-1,\tau-1)(\alpha_{FA,AG} + \alpha_{FA,O}).$$

The annual rate of agricultural conversion (permanent crop) to *Other* land.

$$A_{AG,clear}(t,\tau) = A_{AG}(t-1,\tau-1)(\alpha_{AG,O}).$$

The vegetation re-growth in agriculture for permanent crop is given by:

$A_{AG,new}(t,\tau) = A_{AG}(t,\tau) - diag(diag(A_{AG}(t,\tau))$, where $A_{AG,new}(t,\tau)$ is the same matrix as $A_{AG}(t,\tau)$ without the elements in the diagonal.

A2. Book-keeping carbon cycle model

As described in Ramankutty *et al.* (2007), the following estimates are based on a complete accounting of annual carbon balance.

The carbon density of mature forest C_F, the carbon density of secondary forest C_{SFi} present in 1990 (initial conditions), the carbon density of fallow land C_{FA}, and C_{perm} the carbon density in permanent crop agricultural land can be found in [S1].

<u>*Carbon release from cleared vegetation*</u>

The biomass cleared every year is the sum of biomass from deforestation, cleared secondary vegetation, cleared fallow, and of permanent crop to *Other* land cover :

$$Bio_{Clear}(t) = Bio_{defore}(t) + Bio_{SFclear}(t) + Bio_{FAclear}(t) + Bio_{AGclear}(t) \quad tCyr^{-1}.$$

The biomass cleared from deforestation is:

$$Bio_{defor}(t) = C_F\, D(t) \quad tCyr^{-1},$$

The biomass from re-cleared secondary vegetation is:

$$Bio_{SFclear}(t) = (\sum_{\tau=1}^{t} C_{SF}(\tau-1) S_{SF,clear}(t,\tau)) + C_{SFi} I_{SF,clear}(t) \quad tCyr^{-1}, \text{ where}$$

C_{SF}, the biomass in secondary vegetation created throughout of the simulation, is calculated as follows:

$$C_{SF}(\tau) = \begin{cases} C_F/(1+e^{(1.7-0.105(\tau+5)}) \;\; tCyr^{-1}, if\ \tau < 70\ years \\ C_F\ tCyr^{-1}, if\ \tau \geq 70\ years \end{cases}$$

Note that this biomass is calculated for age-cohort $\tau - 1$ because the cleared biomass has the biomass of the previous year. To be consequential with the fallow definition *in vigor* for Panama (*regrowing vegetation from agricultural land abandonment with less than five years of age*), the land classified as secondary forest is assumed to be more than five years of age, which are added to τ (i.e., τ = 1 for SF is a 5-year old forest). C_{sf} is assumed to be equivalent to the biomass contain in the mature forest after 75 years.

The biomass cleared from the fallow land is:

$$Bio_{FAclear}(t) = C_{FA} \sum_{\tau=1}^{t} A_{FAclear}(t,\tau) \quad tCyr^{-1}.$$

The biomass cleared from the agricultural conversion (permanent crop) to the *Other* land cover is expressed by:

$Bio_{AGclear}(t) = C_{perm} \sum_{\tau=1}^{t} A_{AGclear}(t,\tau) \mathrm{F}_{perm} \quad tCyr^{-1}$, where F_{perm} correspond to the fraction of agricultural land occupied by permanent crop.

The fate of carbon after clearing

The biomass cleared is partitioned into biomass burnt instantaneously (f_{burn}), biomass left as slash on the site (f_{slash}), and biomass transferred to product pools (f_{prod}) as follows:

$f_{burn} = 0.6$; $f_{slash} = 0.339$; $f_{prod} = 0.061$ from Gutierrez, R. (1999).

The various carbon fluxes include flux from instantaneous burning ($C_{f,\ burn}$), flux from decay of product and slash pools ($C_{f,\ decay}$), and flux due to carbon uptake by regrowing vegetation ($C_{regrowth}$).

The burnt flux is calculated as follows:

$$C_{f,burn}(t) = Bio_{clear}(t)\, f_{burn} \quad tCyr^{-1}.$$

Annual transfers of carbon to the slash and product carbon pools are:

$C_{in,slash}(t) = Bio_{clear}(t)\, f_{slash} \quad tCyr^{-1}$, and

$$C_{in,prod}(t) = Bio_{clear}(t)\, f_{prod} \quad tCyr^{-1}$$

The slash and product pools experience exponential decay. Thus, the carbon flux dynamics of the slash and product can be expressed using the differential equation:

$$\frac{dC}{dt} = C_{in} - \lambda C,$$

where C_{in} is the transfer of carbon from deforestation, and λ is the decay rate. Thus, the carbon dynamics for the various pools can be calculated using:

$$C_{slash}(t) = C_{slash}(t-1)(1-\lambda_{slash}) + C_{in,slash}(t) \quad tC \text{, and}$$

$$C_{prod}(t) = C_{prod}(t-1)(1-\lambda_{prod}) + C_{in,prod}(t) \quad tC \text{, and}$$

and the fluxes of carbon from the decay of these pools is calculated as

$$C_{f,decay}(t) = \lambda_{slash} C_{slash}(t-1) + \lambda_{prod} C_{prod}(t-1) \quad tCyr^{-1},$$

where $\lambda_{slash} = 0.1$ and $\lambda_{prod} = 0.1$.

Carbon uptake from re-growing vegetation

The carbon flux from uptake by regrowing secondary forests created after 1990 is:

$$C_{SF,regrowth}(t) = \begin{cases} -\sum_{\tau=1}^{t} A_{SF,new}(t,\tau)\left[C_F/(1+e^{(1.7-0.105(\tau+5))}) - C_F/(1+e^{(1.7-0.105((\tau-1)+5))})\right] tCyr^{-1}, if\ \tau < 70\ yrs \\ 0\ tCyr^{-1}, if\ \tau \geq 70\ yrs \end{cases}$$

The secondary forest present before 1990 as well as newly formed mature forest were accounted to sequester carbon as follow:

$C_{SF,regrowthIC}(t) = -\left[A_{SF,initial}(t)R_{SF} + \sum_{\tau=1}^{t} A_F(t,\tau)R_p\right]\quad tCyr^{-1}$, where R_{SF} is the growth rate in $tCha^{-1}yr^{-1}$ of secondary forest that were already present in 1990 and R_P is the growth rate in $tCha^{-1}yr^{-1}$ of newly classified mature forests, including plantations (according to ANAM land cover classification) [S1].

The carbon uptake resulting from the net fallow re-growth is calculated as:

$$C_{FA,uptake}(t) = -C_{FA}\left[\sum_{\tau=1}^{t} A_{FA}(t,\tau) - \sum_{\tau=1}^{t} A_{FA}(t-1,\tau-1)\right]\ tCyr^{-1}$$

On agricultural land, annual (temporary) crops are assumed to have an annual balance equal to zero (rice, maize, sugarcane). For permanent crops (banana, plantains, coffee, cocoa), the carbon uptake was only considered on newly created agricultural land and calculated as follow:

$$C_{AG,perm}(t) = \begin{cases} -\sum_{\tau=1}^{t} A_{AG,new}\,(t,\tau) F_{perm}\, C_{PermRate} \;\; tCyr^{-1}, if\ \tau \leq 5\ years \\ 0\ tCyr^{-1}, if\ \tau > 5\ years \end{cases}$$, where

F_{perm} correspond to the fraction of agricultural land occupied by permanent crop and $C_{PermRate}$ is the growth rate of permanent crops in $tCha^{-1}yr^{-1}$ [S1].

For pasture land, the carbon uptake by the vegetation was only considered on newly created agricultural land, and the vegetation was assumed to be burned every three years.

$C_{AG,past}(t) = -\left[A_{AG,new}(t,1) F_{past} C_{past}(1 - R_{burn}) \;\; tCyr^{-1}\right]$, where F_{past} is the fraction of agricultural land going to pasture, C_{past} correspond to the carbon contained in the pasture biomass and R_{burn} is the burning frequency ratio.

The total uptake by growing vegetation is than calculated:

$$C_{regrowth}(t) = C_{SF,regrowth}(t) + C_{SF,regrowthIC}(t) + C_{FA,uptake}(t) + C_{AG,perm}(t) + C_{AG,past}(t) \;\; tCyr^{-1}$$

Finally, converted in CO_{2e} (by multiplying the C emissions by 44/12) and expressed in M tons (1 megaton=1,000,000 tons), the total net emissions from land-cover change are calculated as:

$C_{net} = C_{f,burn}(t) + C_{f,decay}(t) + C_{regrowth}(t)\ tCyr^{-1}$.

DETAILS ON METHODS

In order to evaluate net carbon emissions from land-use change in Panama, we adapted a model from Ramankutty *et al.* (2007) (Ramankutty et al., 2007) which includes: a Markov-based model of land-use change and a bookkeeping carbon cycle model. This model was used to project net annual emissions based on historical information from 1990 and 2000. The simulations were performed using MatLab, version 6.1 and 7.6.

Markov model of land-use change

This first-order Markov model served in asserting the land-cover dynamic following deforestation of mature forest (Fearnside and Guimaraes, 1996; Flamm and Turner, 1994; Lambin, 1997; Ramankutty et al., 2007; Wood et al., 1997). This model was constructed using two GIS maps of land use for 1992 and 2000, made available by the National Environment Authority of Panama (ANAM). These maps were based on Landsat TM5 and TM7 images and made in 2002. For the year 1992, a mosaic of eight images was used dating from 1988 to 1992 and from 1998 to 2001 for the year 2000. They constituted the most recent land use analysis for Panama at the time of the study. A life zone map following Holridge's classification (1967) and produced by the Tommy Guardia Geographic Institute of Panama, was used to stratify the country in 8 life zones. Five of the 12 life zones found in Panama were aggregated as they covered small and geographically clustered mountainous areas. The model includes Premontane Moist Forest, Moist Tropical forest, Premontane Wet Forest, Tropical Wet Forest, Premontane Rainforest, Premontane Dry Forest, Tropical Dry Forest, and the aggregated life zones. Only the vector-format of these maps was conserved by ANAM. Only the vector-format was conserved by ANAM. So, the three maps were initially converted from vector to raster with a pixel size of 100 m by 100 m (one hectare) with the Lambert-Azimuthal Equal Area projection, using ArcGIS 9.3 ESRI®. Land use change, including annual deforestation, was evaluated per life zone with matrix calculation on the overlaid maps. Eight contingency tables were built, and transformed into transition probabilities (Equation 1, Appendix 1) (Pastor et al., 1993).

The matrices included five land use classes: Mature forest, Secondary forest, Fallow, Agriculture, and Other (ANAM/ITTO, 2003). Under this classification, the mature forest category includes all forests with more than 80% tree cover as well as plantations. The secondary forest category covers re-growing, previously cleared, and degraded forest having between 60% and 80% tree cover. The fallow category includes re-growing vegetation as part of a shifting cultivation cycle or following agricultural land abandonment, with less than five years of age. The agriculture category was sub-divided into the average percentage area cover with annual crop, permanent crop, and pasture found in Panama's agricultural census (Contraloría, 2001). The "Other" category joined urban areas, inland water (such as lakes or reservoirs), and lowland vegetation liable to flooding (such as albinas). Deforestation was assumed to be zero prior to 1992 for the sake of this modeling exercise.

In order to obtain annual transition probabilities, the eight-root of the matrices were taken when possible. If not, a formula for annualization of matrices was applied (Equation 2, Appendix 1) (Urban and Wallin, 2002). The model was verified using eigenanalysis and bootstrap techniques on the determination of transition matrices (see Equation 3, Appendix 1).

Bookkeeping carbon cycle model

To estimate the flux of carbon related to land-use dynamics, we used a simple bookkeeping carbon cycle model (Houghton, 1999, 2003; Houghton et al., 2000; Ramankutty et al., 2007). This model tracks the annual emissions and uptake following reclearing and regrowth of fallow and secondary forest as well as carbon fluxes from permanent cultivation growth and clearing. Only changes in land use/cover are considered here; changes in land use management or the effect of natural or human disturbances (e.g. fire, insect outbreak) possibly affecting carbon fluxes were not considered. Emissions released following clearing events were partitioned into three pools: 1) a fraction burned whose carbon emissions were considered as immediately lost into the atmosphere,2) a fraction accounting for the decay of residues left on site that are released at slower rate, and 3) a fraction including the carbon temporarily stored in wood products (Gutierrez, 1999). We assumed the same rates of decay for the dead material left on site and for woody material removed from site as were estimated for the Brazilian Amazon (Houghton et al., 2000) because no information is currently available for Panama. Non-CO_2 gases (e.g. methane, nitrous oxide) liberated during the burning process that depend on burning efficiency were not accounted for. Soil carbon changes following land-use change were also ignored in this analysis. It was decided not to account for SOC changes in the model is mainly because of the lack of data availability in Panama. The emissions on soil reported in the greenhouse gases inventory of Panama were basically based on default values and more recent studies showed no statistical differences between forest and pasture, subsistence agriculture, agroforestry systems and plantations (Kirby and Potvin, 2007; Potvin et al., 2004; Schwendenmann and Pendall, 2006; Tschakert et al., 2007). However, none of these studies tracked changes in SOC at the same site through time, which would provide more reliable estimates of changes in SOC with land-use/cover change. Yet, not all transitions have been examined to date (e.g. forest to annual crops).

Average total forest carbon content for the mature forest (including living and dead aboveground and belowground biomass) and the reclearing of secondary forest already present in 1990 was obtained per life zone from Panama's national report to the Forest Resource Assessment of Panama (Gutierrez, 2005) available online at :http://www.fao.org/forestry/fra/50896/en/pan/ (click on Panama). The regrowth and reclearing of secondary forest formed since 1990 were accounted as following a logistic function in proportion to the mature forest mean carbon stock relative to the age of the forest, where exponential growth in trees is considered in the first years (Potvin and Gotelli, 2008) and where we assumed the carbon to be recovered completely after 75 yrs (Alves et al., 1997; Brown and Lugo, 1990) (Equation 4, Appendix 1). Secondary forest regrowth was simulated starting at the age of 5 years in order to correspond to the land use classification, and in particular to distinguish it from the fallow category. Only net changes in annual fallow areas were accounted for; using values from (Gutierrez, 2005). For the reverting mature forest class was assigned a plantation growth rate (Gutierrez, 2005). Mean carbon stock value for the different types of agriculture were used in order to account for the net changes from forest lands to agriculture, without accounting for the changes between the different agricultural land uses themselves. Finally, the annual emissions were obtained per life zone and then summed up to obtain the total national annual emissions. All the equations to the model can be found in SI Model Equations and in Appendix 1 of this document. The variables and parameters used are available in S1.

Sensitivity analysis

We used sensitivity analysis to identify the key parameters having the greatest impact on the overall results by testing specific changes on each parameter. The key results are reported in the main text. For the sensitivity test performed on the land-cover classification accuracy in determining deforested area, the range of value tested comes from (Grassi et al., 2008) which report a range of error of 5 to 20% for mid-resolution imagery and (Foody, 2002) where the commonly recommended overall accuracy is 85% (or less then 15% error). For the quality of the land-cover maps, all the matrices of the Markov model were modified to account for the fact that the time interval between individual images are generally greater than 8 years (Sloan, 2008).The REL was then set to 10-year difference but the model was tested for sensitivity using a 9-year or 8-year time interval. For the snapshot effect, a proportional compensation on four transition probabilities of the Markov matrix was applied, with changes made to the transition from fallow to agriculture and from agriculture to fallow, with proportional change on the transition of fallow to fallow and agriculture to agriculture so that the column would sum up to 1 (Caswell, 2001).

Uncertainty Analysis

Correction of the original data used in the FRA (2005)

The original forest inventory data used for Panama's national report to the FRA (2005) was expressed for the most part in merchantable volume. The data reported in the FRA (2005) were first converted to aboveground living biomass using Brown (1997). Then, different adjustments were performed to account for roots, litter and woody debris depending on the forest class. The belowground biomass was calculated as a fraction of the aboveground living biomass according to default values detailed in the IPCC GPG (2003) corresponding to 0.24 for moist and 0.27 for dry mature forest (Premontane Dry and Tropical Dry Forests), and 0.42 for secondary and fallow classes. The woody debris was calculated as a fraction of the total living biomass according to default value detailed in the IPCC GPG (2003) corresponding to 0.11 for all classes. The biomass data was converted to carbon stock information by multiplying by 0.5. The values presented in table S3 are expressed in terms of tons of C per hectare. Then, as applied in the FRA (2005), the litter was accounted by adding 2.1 for mature forest, 1.7 for secondary forest and, 0.9 for fallow, which was derived from expert knowledge and default factor obtained from the IPCC GPG (2003) (Gutierrez, 2005).

We performed a quantitative analysis of uncertainty using Monte Carlo techniques to propagate uncertainty in the components of the model. It allows us to generate an assessment of uncertainty in the overall results by using key parameters and input variables identified with the sensitivity analysis and to calculate confidence intervals (Verbeeck et al., 2006). For the input parameters uncertainties were given by uniform, normal, lognormal and gamma distributions (S3). A normal distribution was used when suitable for the estimation of symmetrical uncertainties that is where the specified mean value can be assumed more probable than the other values in the range (IPCC, 2000). In this case, the mean and variance was used to generate the normal distribution for mature forest. The lognormal distribution was used for secondary forest; otherwise the high SD relative to the mean would have generated negative values. The gamma distribution was preferred for the fallow carbon stock and was determined with two parameters calculated from (Granger Morgan and Henrion, 1990). Uniform distribution was used when all values in a given range have equal probability, such as the transition matrices and the value used for the fate of carbon. In this case minimum and maximum values were used. For the Markov model, as each column of the matrix has to sum up to one, the main diagonal was defined as the difference of 1 with the sum of the other randomly defined transition probabilities. The ranges of uncertainty around the input parameters was obtained from a thorough review of the literature of Panama (and elsewhere when unavailable in Panama), from the IPCC Good Practice Guidance and, from expert knowledge when no data were available. We simulated the model per life zone by running 10,000 iterations using a Simple Random Sampling (SRS) of parameter values within defined ranges. While in other studies, correlations between parameters emerged as very influential component of uncertainty (Peltoniemi et al., 2006; Smith and Heath, 2001), for this model key parameters and input variables are assumed to be correlated through time but independent between the different iterations of the Monte Carlo analysis. We made no distinction between the uncertainty due to lack of knowledge and the uncertainty caused by natural variability. In order to make this distinction, a second-order Monte Carlo analysis should be applied (Hoffman and Hammonds, 1994; Verbeeck et al., 2006). However, we recognize our inability to partition these two components because of the lack information currently available.

We evaluated the 95% confidence intervals per life zone. To propagate the error on the overall results, we added the mean and the variance obtained for each life zone and calculated the total mean and the 95% confidence intervals (Granger Morgan and

Henrion, 1990; Hammonds et al., 1994). We did not address possible additional uncertainty due to the model structure as this uncertainty should be examined by alternative models or by the addition of parameters that were not included in the model (Hammonds et al., 1994).

Scenario Analysis

We used this model to see the effect of different possible strategies to reduce emissions from deforestation that could be of interest to the government of Panama. After ample discussions with civil servants and assisting to different workshops given on REDD in Panama, five scenarios of deforestation reduction were selected. These scenarios include 1) the Mesoamerican Biological Corridor of Atlantic Panama phase II conservation project (CBMAP II scenario), 2) the National System of Protected Areas including 54 protected areas (SINAP scenario), 3) the Palo Seco forest reserve, a priority protected area for ANAM and the Darien biogeographical region where high level of deforestation are in effect (Palo Seco & Darién scenario, 4) the replication of Ipetí-Emberá REDD community project in other communities of Darien region (Replication of Ipetí-Emberá scenario), and 5) a reduction of 50% of the annual deforestation (Stern Review). We tested the different scenarios from the year 2000 to 2030, starting the reduction of deforestation in 2010.

Appendix 1. *Equations*

Equation 1. Obtention of transition probabilities

Eight contingency tables were built, and transformed into transition probabilities (Pastor et al., 1993).

1)

$$p_{i,j,\tau} = n_{i,j}/\sum_{j=1}^{m} n_{i,j}$$

where $p_{ij,t}$ is the probability of one hectare to change from land use *i* to *j* during the time *t*

Equation 2. Annualization of matrices

2) $$p_{i,j} = p_{ij,\tau}/t$$

where $p_{i,j}$ is the off-diagonal probability,

$p_{i,i} = 1 - sum(p_{i,j})$ for j=1 to n,

where $p_{i,i}$ is the diagonal probability

Validation of the annualization of the transition matrices

The validity of the annualization of the transition matrices using Equation 2 described above, was verified by running the model starting in 1990 to compare the value from the simulations with the area cover by each land use in 2000. An eigenanalysis was performed between the annual matrices and the ten-year matrices to verify the effect of annualizing the matrices (Tanner et al., 1994). The eigenvalues, right and left eigenvectors as well as the Damping ratio sensitivity of the transition probability matrices were calculated (Caswell, 2001; Wootton, 2001) (Equation 3 below) , and were consistent between the annual and the ten-year matrices.

Equation 3.

$$\frac{d\rho}{dp_{jk}} = \frac{1}{|\lambda_2|}\left[\frac{d\lambda_1}{dp_{jk}} - \frac{\rho}{|\lambda_2|}\left(x\frac{dx}{dp_{jk}} + y\frac{dy}{dp_{jk}}\right)\right] \; where \; \frac{d\lambda_1}{dp_{jk}} = \frac{v_j w_k}{(v_1, w_1)}$$

$$\frac{dx}{dp_{jk}} \; and \; \frac{dy}{dp_{jk}} \; are \; the \; real \; and \; imaginary \; parts \; of \; \frac{d\lambda_2}{dp_{jk}} \; respectively$$

(v_1, w_1) is the inner product of the right and left eigenvectors.

Equation 4. Logistic equation

The function used to calculate the standing stock of the secondary forest is

$Csf = Cveg / (1+e^{1.7-0.105(t)})$

where t is time in years,

Cveg is the standing stock in mature forest,

Csf the standing stock in secondary forest

The reverting rate is calculated as $\Delta Csf = f(t) - f(t-1)$.

S1. Parameter and carbon values used in the model

	Value	Unit
Premontane Moist Forest		
Mature forest	164.4	tC/ha
Secondary forest	117.5	tC/ha
Fallow	51.9	tC/ha
Area deforested	491	ha
Fraction of the deforested land to secondary forest	0.310	-
Fraction of the deforested land to fallow	0.216	-
Fraction of the deforested land to agriculture	0.195	-
Fraction of the deforested land to other	0.279	-
Initial condition A_F	17574	-
Initial condition A_{SF}	7872	-
Initial condition A_{FA}	34458	-
Initial condition A_{AG}	170415	-
Initial condition A_O	7515	-
Moist Tropical forest		
Mature forest	177.5	tC/ha
Secondary forest	128.4	tC/ha
Fallow	56.7	tC/ha
Area deforested	21700	ha
Fraction of the deforested land to secondary forest	0.312	-
Fraction of the deforested land to fallow	0.307	-
Fraction of the deforested land to agriculture	0.353	-
Fraction of the deforested land to other	0.028	-
Initial condition A_F	1221316	-
Initial condition A_{SF}	224564	-
Initial condition A_{FA}	407206	-
Initial condition A_{AG}	1070153	-
Initial condition A_O	40704	-
Premontane Wet Forest		
Mature forest	176.8	tC/ha
Secondary forest	138.2	tC/ha
Fallow	61.1	tC/ha
Area deforested	5597	ha
Fraction of the deforested land to secondary forest	0.258	-
Fraction of the deforested land to fallow	0.309	-
Fraction of the deforested land to agriculture	0.427	-
Fraction of the deforested land to other	0.006	-
Initial condition A_F	637773	-
Initial condition A_{SF}	162373	-
Initial condition A_{FA}	215423	-
Initial condition A_{AG}	344750	-
Initial condition A_O	556	-
Tropical Wet Forest		
Mature forest	178.6	tC/ha
Secondary forest	126.4	tC/ha

Fallow	55.9	tC/ha
Area deforested	11544	ha
Fraction of the deforested land to secondary forest	0.489	-
Fraction of the deforested land to fallow	0.103	-
Fraction of the deforested land to agriculture	0.406	-
Fraction of the deforested land to other	0.002	-
Initial condition A_F	1069260	-
Initial condition A_{SF}	186597	-
Initial condition A_{FA}	185863	-
Initial condition A_{AG}	164522	-
Initial condition A_O	1358	-
Premontane Rainforest		
Mature forest	171.8	tC/ha
Secondary forest	121.6	tC/ha
Fallow	53.8	tC/ha
Area deforested	3135	ha
Fraction of the deforested land to secondary forest	0.459	-
Fraction of the deforested land to fallow	0.161	-
Fraction of the deforested land to agriculture	0.378	-
Fraction of the deforested land to other	0.002	-
Initial condition A_F	532993	-
Initial condition A_{SF}	53129	-
Initial condition A_{FA}	33067	-
Initial condition A_{AG}	51911	-
Initial condition A_O	326	-
Premontane Dry Forest		
Mature forest	169.1	tC/ha
Secondary forest	114.0	tC/ha
Fallow	50.4	tC/ha
Area deforested	10	ha
Fraction of the deforested land to secondary forest	0.141	-
Fraction of the deforested land to fallow	0.129	-
Fraction of the deforested land to agriculture	0.149	-
Fraction of the deforested land to other	0.580	-
Initial condition A_F	12212	-
Initial condition A_{SF}	134	-
Initial condition A_{FA}	2097	-
Initial condition A_{AG}	35817	-
Initial condition A_O	8941	-
Tropical Dry Forest		
Mature forest	165.6	tC/ha
Secondary forest	114.0	tC/ha
Fallow	50.4	tC/ha
Area deforested	67	ha
Fraction of the deforested land to secondary forest	0.363	-
Fraction of the deforested land to fallow	0.152	-
Fraction of the deforested land to agriculture	0.227	-
Fraction of the deforested land to other	0.258	-

Initial condition A_F	5076	-
Initial condition A_{SF}	3110	-
Initial condition A_{FA}	22670	-
Initial condition A_{AG}	236178	-
Initial condition A_O	7518	-
Mountainous life zones		
Mature forest	163.8	tC/ha
Secondary forest	116.0	tC/ha
Fallow	49.1	tC/ha
Area deforested	418	ha
Fraction of the deforested land to secondary forest	0.369	-
Fraction of the deforested land to fallow	0.198	-
Fraction of the deforested land to agriculture	0.417	-
Fraction of the deforested land to other	0.016	-
Initial condition A_F	184522	-
Initial condition A_{SF}	7737	-
Initial condition A_{FA}	7854	-
Initial condition A_{AG}	14022	-
Initial condition A_O	0	-
Parameter used for all life zones		
Rate of accumulation for mature forest (here representing plantations)	4.3	tC/ha/yr
Rate of accumulation for secondary forest	3.4	tC/ha/yr
Pasture	4.8	tC/ha
Permanent crops (for all Moist and Wet life zones)*	50	tC/ha
Rate of accumulation for permanent crop (for all Moist and Wet life zones)	10	tC/ha/yr
Permanent crops (for Dry Tropical Forest and Dry Premontane Forest)**	21	tC/ha
Rate of accumulation for permanent crop (for Dry Tropical Forest and Dry Premontane Forest)	2.6	tC/ha/yr
Fraction of the carbon that is emitted through burning	0.6	-
Fraction of the carbon that goes in the slash pool	0.34	-
Fraction of the carbon that goes in the product pool	0.06	-

* Assumes a five-year harvest cycle/maturity (Table 3.3.2, IPCC Good Practice Guidance from Schroeder (1994)).

** Assumes an eight-year harvest cycle/maturity (Table 3.3.2, IPCC Good Practice Guidance from Schroeder (1994)).

S2. The land-use change transition matrices

Premontane Moist Forest

		1992				
		forest	secondary	fallow	agriculture	other
2000	forest	0.967134	0.003631	0.000445	0.000202	0.002480
	secondary	0.010529	0.965731	0.030695	0.002212	0.000639
	fallow	0.010150	0.021784	0.866151	0.036966	0.002456
	agriculture	0.002362	0.005690	0.099860	0.960112	0.017421
	other	0.009823	0.003164	0.002848	0.000508	0.977004

Moist Tropical forest

		1992				
		forest	secondary	fallow	agriculture	other
2000	forest	0.976649	0.017081	0.007086	0.000442	0.005424
	secondary	0.008015	0.932271	0.039189	0.001931	0.003213
	fallow	0.006863	0.034633	0.901479	0.053949	0.004955
	agriculture	0.007930	0.015849	0.049009	0.942816	0.006391
	other	0.000543	0.000167	0.003237	0.000863	0.980017

Premontane Wet Forest

		1992				
		forest	secondary	fallow	agriculture	other
2000	forest	0.987180	0.012279	0.004157	0.002287	0.037590
	secondary	0.003303	0.952479	0.029267	0.010406	0.002518
	fallow	0.003959	0.022488	0.941115	0.024752	0.002518
	agriculture	0.005479	0.012633	0.025038	0.962206	0.026619
	other	0.000080	0.000122	0.000423	0.000350	0.930755

Tropical Wet Forest

		1992				
		forest	secondary	fallow	agriculture	other
2000	forest	0.988332	0.006412	0.006245	0.005035	0.041016
	secondary	0.005702	0.962927	0.031197	0.016539	0.013476
	fallow	0.001207	0.020696	0.938911	0.026491	0.004050
	agriculture	0.004736	0.009903	0.023484	0.951596	0.021649
	other	0.000023	0.000062	0.000162	0.000339	0.919809

Premontane Rainforest

		1992				
		forest	secondary	fallow	agriculture	other
2000	forest	0.993634	0.007636	0.007173	0.004643	0.004601
	secondary	0.002925	0.949103	0.025739	0.013292	0.000613
	fallow	0.001024	0.025984	0.931488	0.019928	0
	agriculture	0.002404	0.017190	0.035434	0.962018	0
	other	0.000013	0.000087	0.000166	0.000119	0.994785

Premontane Dry Forest

1992

		forest	secondary	fallow	agriculture	other
2000	forest	0.990182	0.011194	0.005198	0.001617	0.004653
	secondary	0.001384	0.913433	0.014497	0.003401	0
	fallow	0.001269	0.014179	0.922413	0.023327	0.001398
	agriculture	0.001466	0.020896	0.038674	0.959687	0.002863
	other	0.005699	0.040299	0.019218	0.011969	0.991086

Tropical Dry Forest

				1992		
		forest	secondary	fallow	agriculture	other
2000	forest	0.970173	0.004534	0.001610	0.000124	0.002368
	secondary	0.010816	0.960193	0.018734	0.003080	0.001955
	fallow	0.004531	0.011961	0.922894	0.013609	0.010335
	agriculture	0.006777	0.021704	0.054905	0.981456	0.036113
	other	0.007703	0.001608	0.001857	0.001730	0.949229

Aggregated life zones

				1992		
		forest	secondary	fallow	agriculture	other
2000	forest	0.995792	0.040158	0.010810	0.003330	0
	secondary	0.001552	0.929546	0.021861	0.016274	0
	fallow	0.000833	0.017991	0.927769	0.009100	0
	agriculture	0.001756	0.011167	0.034899	0.961339	0
	other	0.000068	0.001137	0.004660	0.009956	1

S3. Data used in the Monte Carlo analysis.

Premontane Moist Forest		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	207.0	
PNUD/FAO, 1972	163.2	
PNUD/FAO, 1972	180.2	
PNUD/FAO, 1972	160.3	
NA	141.3	
NA	138.2	
Mean		**165.0**
SD		**25.7**
Probability distribution function		**Normal**
Secondary forest		
Mean*		**115.6**
SD†		**18.0**
Probability distribution function		**Lognormal**
Rastrojo‡		
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**
Moist Tropical forest		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	207.9	
PNUD/FAO, 1972	163.2	
PNUD/FAO, 1972	159.4	
PNUD/FAO, 1972	134.6	
PNUD/FAO, 1972	138.2	
PNUD/FAO, 1972	192.2	
PNUD/FAO, 1972	167.2	
PNUD/FAO, 1972	150.3	
PNUD/FAO, 1972	132.2	
PNUD/FAO, 1972	193.2	
PNUD/FAO, 1972	146.6	
PNUD/FAO, 1972	303.6	
PNUD/FAO, 1972	175.3	
PNUD/FAO, 1972	242.2	
PNUD/FAO, 1972	254.6	
PNUD/FAO, 1972	182.5	
Aserradero Los Cuatro Hermanos, 1998	161.9	
EXTRAFORSA, 1992	133.9	
Maderas Pacaro, S. A., 1991	192.5	
Corporación Síntesis, S. A., 1996	200.4	
Castillo, A., 1991	213.4	

Aserradero Chagres, S. A., 1991	190.9	
Pegui, S. A., 1992	197.9	
Mederas del Tesca, S. A., 199_?	200.7	
Aserradero Los Cuatro Hermanos, S. A., 1992	157.2	
Madera de Subcurtí, S. A., 1992	186.0	
ANCON, 1998	161.7	
Grupo Melo, S. A., 199_?	156.7	
Maderas del Darién, S. A., 199_?	165.5	
Laminados Mon, S. A., 1993	180.8	
Yaviza en Marcha, S. A., 199_?	176.5	
Kirby & Potvin (2007)	317.0	
Magallon, F. Master Thesis (2002)	181.0	
Mean		**185.4**
SD		**43.0**
Probability distribution function		**Normal**

Secondary forest

Source	Total C stock (in tC/ha)	
ANAM, 1998	161.1	
ANAM, 1998	161.1	
ANAM, 1998	172.2	
ANAM, 1998	171.4	
INRENARE, 1998	148.2	
PNUD/FAO, 1972	147.1	
PNUD/FAO, 1972	103.0	
PNUD/FAO, 1972	109.8	
PNUD/FAO, 1972	97.5	
PNUD/FAO, 1972	74.3	
PNUD/FAO, 1972	83.1	
Mean		**129.9**
SD		**36.8**
Probability distribution function		**Lognormal**

Rastrojo[‡]

Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	60.2	*not used*
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**

Premontane Wet Forest

Mature forest

Source	Total C stock (in tC/ha)
PNUD/FAO, 1972	212.8
PNUD/FAO, 1972	169.8
NA	74.1
Centro Científico Tropical, 1995	135.5

Inversiones Hope, 199_	305.7	
Mean		**179.6**
SD		**86.8**
Probability distribution function		**Lognormal**
Secondary forest		
Source	Total C stock (in tC/ha)	
Centro Científico Tropical, 1995	82.0	
Centro Científico Tropical, 1995	113.4	
PNUD/FAO, 1972	84.2	
Mean		**93.2**
SD		**17.5**
Probability distribution function		**Lognormal**
Rastrojo‡		
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**
Tropical Wet Forest		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	207.0	
PNUD/FAO, 1972	180.2	
PNUD/FAO, 1972	160.3	
PNUD/FAO, 1972	151.8	
PNUD/FAO, 1972	184.3	
PNUD/FAO, 1972	132.9	
PNUD/FAO, 1972	216.5	
PNUD/FAO, 1972	161.5	
Reforestadora el Zapallal, S. A., 1998	188.8	
JICA, 1995	176.5	
Naturaleza y Desarrollo, S. A., 1998	188.9	
INRENARE/OIMT, 1997	187.0	
Mean		178.0
SD		23.3
Probability distribution function		**Normal**
Secondary forest		
Source	Total C stock (in tC/ha)	
JICA, 1985	125.1	
JICA, 1985	106.7	
JICA, 1985	124.4	
JICA, 1985	132.3	
PNUD/FAO, 1972	145.0	
PNUD/FAO, 1972	119.2	
JICA, 1985	98.2	
Mean		**121.5**

SD		**15.6**
Probability distribution function		**Lognormal**
Rastrojo		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	40.3	
PNUD/FAO, 1972	5.1	
Mean (parameter A for scale)	**22.7**	0.8
SD (parameter B for the shape)	**24.9**	27.3
Probability distribution function		**Gamma**
Premontane Rainforest		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	159.9	
PNUD/FAO, 1972	133.2	
PNUD/FAO, 1972	192.3	
PNUD/FAO, 1972	214.1	
PNUD/FAO, 1972	150.4	
PNUD/FAO, 1972	141.0	
Mean		**165.1**
SD		**31.6**
Probability distribution function		**Normal**
Secondary forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	102.7	
PNUD/FAO, 1972	82.5	
PNUD/FAO, 1972	82.9	
PNUD/FAO, 1972	147.2	
Mean		**103.8**
SD		**30.4**
Probability distribution function		**Lognormal**
Rastrojo		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	48.4	
PNUD/FAO, 1972	17.0	
Mean (parameter A for scale)	**32.7**	2.2
SD (parameter B for the shape)	**22.1**	15.0
Probability distribution function		**Gamma**
Premontane Dry Forest		
Mature forest		
Mean§		**147.3**
SD¶		**1.8**
Probability distribution function		**Normal**

Secondary forest		
Mean[‖]		**115.7**
SD[**]		**36.6**
Probability distribution function		**Lognormal**
Rastrojo[‡]		
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**
Tropical Dry Forest		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	167.1	
PNUD/FAO, 1972	163.2	
PNUD/FAO, 1972	166.4	
Mean		**165.6**
SD		**2.1**
Probability distribution function		**Normal**
Secondary forest		
Source	Total C stock (in tC/ha)	
ANAM/USAID/STRI, 1999	169.5	
PNUD/FAO, 1972	87.3	
PNUD/FAO, 1972	133.4	
Mean		**130.1**
SD		**41.2**
Probability distribution function		**Lognormal**
Rastrojo[‡]		
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**
Mountainous life zones		
Mature forest		
Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	192.3	
PNUD/FAO, 1972	129.1	
PNUD/FAO, 1972	189.1	
PNUD/FAO, 1972	140.3	
PNUD/FAO, 1972	189.1	
PNUD/FAO, 1972	140.3	
PNUD/FAO, 1972	108.1	
Mean		**155.5**
SD		**34.2**
Probability distribution function		**Normal**
Secondary forest		

Source	Total C stock (in tC/ha)	
PNUD/FAO, 1972	123.1	
Mean		**123.1**
SD[†]		**27.1**
Probability distribution function		**Lognormal**
Rastrojo[‡]		
PNUD/FAO, 1972	60.8	*not used*
Mean (parameter A for scale)	**38.6**	2.8
SD (parameter B for the shape)	**23.0**	13.7
Probability distribution function		**Gamma**
Parameter used for all life zones		
	Minimum	**Maximum**
Fate of carbon		
fburn	0.2	0.6
fslash	0.339	0.7
fprod	0.061	0.1
Premontane Moist Forest		
*f,sf * †*	0.010529	0.013102
f,fa	0.01015	0.012468
f,ag	0.002362	0.003128
f,o	0.009823	0.012203
sf,f	0.003631	0.004503
sf,fa	0.021784	0.026674
sf.ag	0.00569	0.007413
sf,o	0.003164	0.003943
fa,f	0.000445	0.000567
fa,sf	0.030695	0.037563
fa,ag	0.09986	0.204721
fa,o	0.002848	0.003512
ag,f	0.000202	0.000254
ag,sf	0.002212	0.002926
ag,fa	0.036966	0.064931
ag,o	0.000508	0.000649
o,f	0.00248	0.00308
o,sf	0.000639	0.000815
o,fa	0.002456	0.00312
o,ag	0.017421	0.021641
Moist Tropical forest		
f,sf	0.008015	0.009948
f,fa	0.006863	0.008558
f,ag	0.00793	0.009886
f,o	0.000543	0.00068
sf,f	0.017081	0.021144
sf,fa	0.034633	0.042516
sf.ag	0.015849	0.019794
sf,o	0.000167	0.000228
fa,f	0.007086	0.008834

fa,sf	0.039189	0.047954
fa,ag	0.049009	0.065669
fa,o	0.003237	0.003993
ag,f	0.000442	0.000614
ag,sf	0.001931	0.002725
ag,fa	0.053949	0.064698
ag,o	0.000863	0.001096
o,f	0.005424	0.006757
o,sf	0.003213	0.004011
o,fa	0.004955	0.006179
o,ag	0.006391	0.007964
Premontane Wet Forest		
f,sf	0.003303	0.004128
f,fa	0.003959	0.004949
f,ag	0.005479	0.006848
f,o	7.98E-05	9.98E-05
sf,f	0.012279	0.015349
sf,fa	0.022488	0.02811
sf.ag	0.012633	0.015791
sf,o	0.000122	0.000152
fa,f	0.004157	0.005196
fa,sf	0.029267	0.036584
fa,ag	0.025038	0.050076
fa,o	0.000423	0.000529
ag,f	0.002287	0.002858
ag,sf	0.010406	0.013007
ag,fa	0.024752	0.040397
ag,o	0.00035	0.000438
o,f	0.03759	0.046987
o,sf	0.002518	0.003147
o,fa	0.002518	0.003147
o,ag	0.026619	0.033273
Tropical Wet Forest		
f,sf	0.005702	0.007128
f,fa	0.001207	0.001508
f,ag	0.004736	0.005921
f,o	2.29E-05	2.86E-05
sf,f	0.006412	0.008015
sf,fa	0.020696	0.02587
sf.ag	0.009903	0.012379
sf,o	6.22E-05	7.77E-05
fa,f	0.006245	0.007807
fa,sf	0.031197	0.038996
fa,ag	0.023484	0.04294
fa,o	0.000162	0.000202
ag,f	0.005035	0.006293
ag,sf	0.016539	0.020674
ag,fa	0.026491	0.04847
ag,o	0.000339	0.000424
o,f	0.041016	0.05127

o,sf	0.013476	0.016845
o,fa	0.00405	0.005063
o,ag	0.021649	0.027062
Premontane Rainforest		
f,sf	0.002925	0.003656
f,fa	0.001024	0.00128
f,ag	0.002404	0.003005
f,o	1.29E-05	1.62E-05
sf,f	0.007636	0.009545
sf,fa	0.025984	0.03248
sf.ag	0.01719	0.021488
sf,o	8.66E-05	0.000108
fa,f	0.007173	0.008967
fa,sf	0.025739	0.032173
fa,ag	0.035434	0.051178
fa,o	0.000166	0.000208
ag,f	0.004643	0.005803
ag,sf	0.013292	0.016615
ag,fa	0.019928	0.029957
ag,o	0.000119	0.000149
o,f	0.004601	0.005752
o,sf	0.000613	0.000767
o,fa	0	0
o,ag	0	0
Premontane Dry Forest		
f,sf	0.001384	0.00173
f,fa	0.001269	0.001587
f,ag	0.001466	0.001832
f,o	0.005699	0.007124
sf,f	0.011194	0.013993
sf,fa	0.014179	0.017724
sf.ag	0.020896	0.026119
sf,o	0.040299	0.050373
fa,f	0.005198	0.006497
fa,sf	0.014497	0.018121
fa,ag	0.038674	0.049881
fa,o	0.019218	0.024022
ag,f	0.001617	0.002021
ag,sf	0.003401	0.004251
ag,fa	0.023327	0.029159
ag,o	0.011969	0.014961
o,f	0.004653	0.005816
o,sf	0	0
o,fa	0.001398	0.001748
o,ag	0.002863	0.003579
Tropical Dry Forest		
f,sf	0.010816	0.01352
f,fa	0.004531	0.005664
f,ag	0.006777	0.008471
f,o	0.007703	0.009629

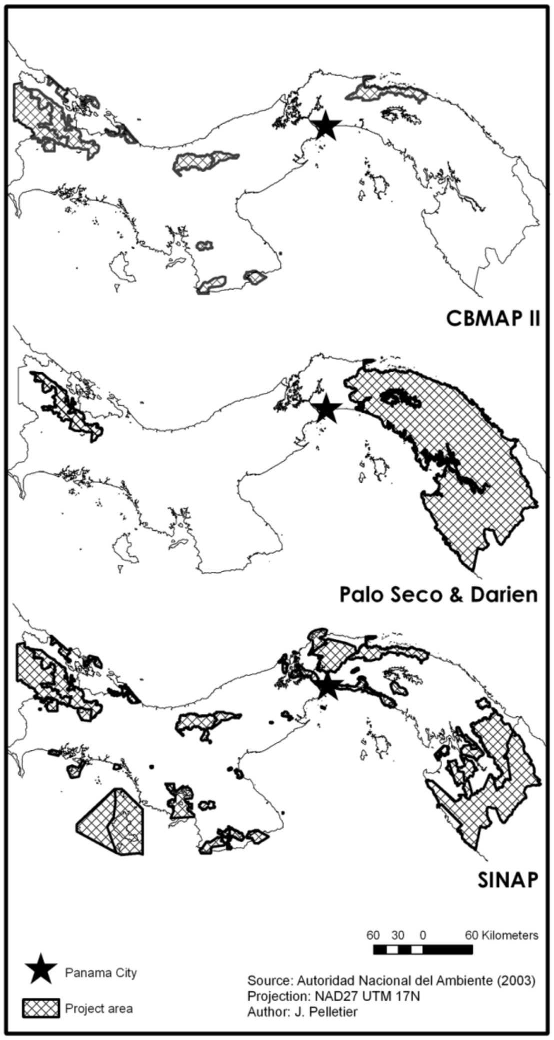
sf,f	0.004534	0.005667
sf,fa	0.011961	0.014952
sf.ag	0.021704	0.02713
sf,o	0.001608	0.00201
fa,f	0.00161	0.002013
fa,sf	0.018734	0.023418
fa,ag	0.054905	0.08294
fa,o	0.001857	0.002321
ag,f	0.000124	0.000156
ag,sf	0.00308	0.00385
ag,fa	0.013609	0.018384
ag,o	0.00173	0.002163
o,f	0.002368	0.00296
o,sf	0.001955	0.002444
o,fa	0.010335	0.012919
o,ag	0.036113	0.045142
Mountainous life zones		
f,sf	0.001552	0.001939
f,fa	0.000833	0.001041
f,ag	0.001756	0.002195
f,o	6.77E-05	8.47E-05
sf,f	0.040158	0.050197
sf,fa	0.017991	0.022489
sf.ag	0.011167	0.013959
sf,o	0.001137	0.001422
fa,f	0.01081	0.013512
fa,sf	0.021861	0.027327
fa,ag	0.034899	0
fa,o	0.00466	0.005825
ag,f	0.00333	0.004163
ag,sf	0.016274	0.020343
ag,fa	0.0091	0
ag,o	0.009956	0.012445
o,f	0	0
o,sf	0	0
o,fa	0	0
o,ag	0	0

* Mean was scaled relative to the difference observed between Mature forest and secondary forest in the Moist Tropical Forest, in proportion to the mean obtained for the mature forest of the same life zone.

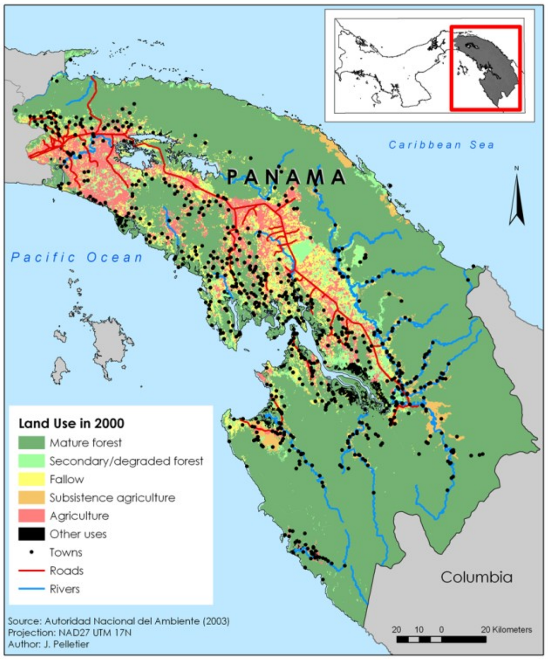
† SD is calculated as proportional to the SD in mature forest for the same life zone.
‡ The mean and SD used was calculated from all available fallow inventory data from the FRA (2005).
§Mean was estimated according to the difference observed between Moist Tropical forest and Premontane Moist forest, in proportion to the mean obtained for the mature forest in the Tropical Dry Forest

¶ SD was calculated in proportion to SD found in mature tropical dry forest.
|| Mean was estimated relative to difference observed between mature and secondary forest in the tropical dry life zone, in proportion to the mean obtained for the mature forest of the same life zone. .

** SD was calculated in proportion to SD found in secondary tropical dry forest



S4. Area covered by the scenarios of deforestation reduction CBMAP II, Palo Seco & Darien, and SINAP scenarios. The Palo Seco & Darien scenario covers the same area as the CBMAP II, though the area was selected randomly on a per pixel basis in the Darién biogeographical region (pixel of 100 m per 100 m).



S5. Population centroids located in the Darién biogeographical region in proximity of mature forests in 2000 and accounted for in the Replication of Ipetí-Emberá project scenario.

REFERENCES CITED:

Alves, D.S., Soares, J.V., Amaral, S., Mello, E.M.K., Almeida, S.A.S., DaSilva, O.F., Silveira, A.M. (1997) Biomass of primary and secondary vegetation in Rondonia, Western Brazilian Amazon. Global Change Biology 3, 451-461.

ANAM/ITTO, (2003) Informe final de resultados de la cobertura boscosa y uso del suelo de la Republica de Panama: 1992-2000. Autoridad Nacional del Ambiente, Panama, Republica de Panama, p. 107 pp.

Brown, S., Lugo, A.E. (1990) Tropical Secondary Forests. Journal of Tropical Ecology 6, 1-32.

Caswell, H. (2001) Matrix population models: construction, analysis, and interpretation, 2nd ed. ed. Sinauer Associates, Inc., Sunderland, MA.

Contraloría, (2001) VI Censo Agropecuario. Contraloría General de la República - Dirección de Estadística y Censo República de Panamá.

Fearnside, P.M., Guimaraes, W.M. (1996) Carbon uptake by secondary forests in Brazilian Amazonia. Forest Ecology and Management 80, 35-46.

Flamm, R.O., Turner, M.G. (1994) Alternative Model Formulations for a Stochastic Simulation of Landscape Change. Landscape Ecology 9, 37-46.

Foody, G.M. (2002) Status of land cover classification accuracy assessment. Remote Sensing of Environment 80, 185-201.

Granger Morgan, M., Henrion, M. (1990) Uncertainty, A guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. . Cambridge University Press, New York.

Grassi, G., Monni, S., Federici, S., Achard, F., Mollicone, D. (2008) Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates. Environmental Research Letters 3, 035005 (035012pp.).

Gutierrez, R., (1999) Inventario Nacional de Gases de Efecto Invernadero para el modulo “Cambio de Uso de la Tierra y Silvicultura”. , in: ANAM (Ed.). República de Panamá, Panamá, p. 115 pp.

Gutierrez, R., (2005) Forest Resource Assessment 2005: Country report Panama. Food and Agriculture Organization-Forest Department, Rome, p. 118p.

Hammonds, J.S., Hoffman, F.O., Bartell, S.M., (1994) An Introductory Guide to Uncertainty Analysis in Environmental and Health Risk Assessment, in: SENES Oak Ridge, I. (Ed.). Oak Ridge National Laboratory, Oak Ridge, Tennessee, p. 34.

Hoffman, F.O., Hammonds, J.S. (1994) Propagation of Uncertainty in Risk Assessments - The Need To Distinguish Between Uncertainty Due to Lack of Knowledge and Uncertainty Due to Variability. Risk Analysis 14, 707-712.

Houghton, R.A. (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus Series B-Chemical and Physical Meteorology 51, 298-313.

Houghton, R.A. (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus Series B-Chemical and Physical Meteorology 55, 378-390.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H. (2000) Annual fluxes or carbon from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301-304.

IPCC, (2000) Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. . IPCC/OECD/IEA/IGES, Hayana, Japan.

Kirby, K.R., Potvin, C. (2007) Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. Forest Ecology and Management 246, 208-221.

Lambin, E.F. (1997) Modelling and monitoring land-cover change processes in tropical region. Progress in Physical Geography 21, 375-393.

Pastor, J., Bonde, J., Johnston, C., Naiman, R.J. (1993) Markovian analysis of the spatially dependent dynamics of beaver ponds. Lectures on Mathematics in the Life Sciences 23, 5-27.

Peltoniemi, M., Palosuo, T., Monni, S., Makipaa, R. (2006) Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation. Forest Ecology and Management 232, 75-85.

Potvin, C., Gotelli, N.J. (2008) Biodiversity enhances individual performance but does not affect survivorship in tropical trees. Ecology Letters 11, 217-223.

Potvin, C., Whidden, E., Moore, T. (2004) A case study of carbon pools under three different land-uses in Panama. Climatic Change 67, 291-307.

Ramankutty, N., Gibbs, H.K., Achard, F., Defries, R., Foley, J.A., Houghton, R.A. (2007) Challenges to estimating carbon emissions from deforestation. Global Change Biology 13, 51-66.

Schwendenmann, L., Pendall, E. (2006) Effects of forest conversion into grassland on soil aggregate structure and carbon storage in Panama: evidence from soil carbon fractionation and stable isotopes. Plant and Soil 288, 217-232.

Sloan, S. (2008) Reforestation amidst deforestation: Simultaneity and succession. Global Environmental Change 18, 425-441

Smith, J.E., Heath, L.S. (2001) Identifying influences on model uncertainty: An application using a forest carbon budget model. Environmental Management 27, 253-267.

Tanner, J.E., Hughes, T.P., Connell, J.H. (1994) Species Coexistence, Keystone Species, and Succession - a Sensitivity Analysis. Ecology 75, 2204-2219.

Tschakert, P., Coomes, O.T., Potvin, C. (2007) Indigenous livelihoods, slash-and-burn agriculture, and carbon stocks in Eastern Panama. Ecological Economics 60, 807-820.

Urban, D.L., Wallin, D.O., (2002) Introduction to Markov Models., in: Gergel, S.E., Turner, M.G. (Eds.), Learning landscape ecology: a practical guide to concepts and techniques. Springer-Verlag, New York, p. 316 pp.

Verbeeck, H., Samson, R., Verdonck, F., Lemeur, R. (2006) Parameter sensitivity and uncertainty of the forest carbon flux model FORUG: a Monte Carlo analysis. Tree Physiology 26, 807-817.

Wood, E.C., Lewis, J.E., Tappan, G.G., Lietzow, R.W. (1997) The Development of a Land Cover Change Model for Southern Senegal., Sioux Falls, South Dakota.

Wootton, J.T. (2001) Prediction in complex communities: Analysis of empirically derived Markov models. Ecology 82, 580-598.