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Diagnosing the uncertainty and detectability of emission reductions for REDD+ under current capabilities: an example for Panama

Johanne Pelletier^{1,4}, Navin Ramankutty² and Catherine Potvin^{1,3}

¹ Department of Biology and Global Environmental and Climate Change Center, McGill University, 1205 Dr Penfield, Montreal, QC, H3A 1B1, Canada

² Department of Geography and Global Environmental and Climate Change Center, McGill University, 805 Sherbrooke Street W., Montreal, QC, H3A 2K6, Canada

³ Smithsonian Tropical Research Institute, Apartado 2072, Balboa, Panama

E-mail: johannepelletier@gmail.com

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Abstract

In preparation for 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, and 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, for developing countries involved in REDD+, for improving the accuracy of their estimates in the future. These new considerations confirm the importance of current efforts to establish forest monitoring systems and enhance capabilities for REDD+ in developing countries.

Keywords: reducing emissions from deforestation and forest degradation in developing countries (REDD+), uncertainty analysis, tropical deforestation, emission reductions, developing countries

 Online supplementary data available from stacks.iop.org/ERL/6/024005/mmedia

⁴ Author to whom any correspondence should be addressed.

1. 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 16th 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 2009).

The GOFCC-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 (GOFCC-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.

1.1. Panama's national context

Panama is a small country with an area of circa 74 500 km² 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 2000–10 (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+.

2. 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 supplementary information

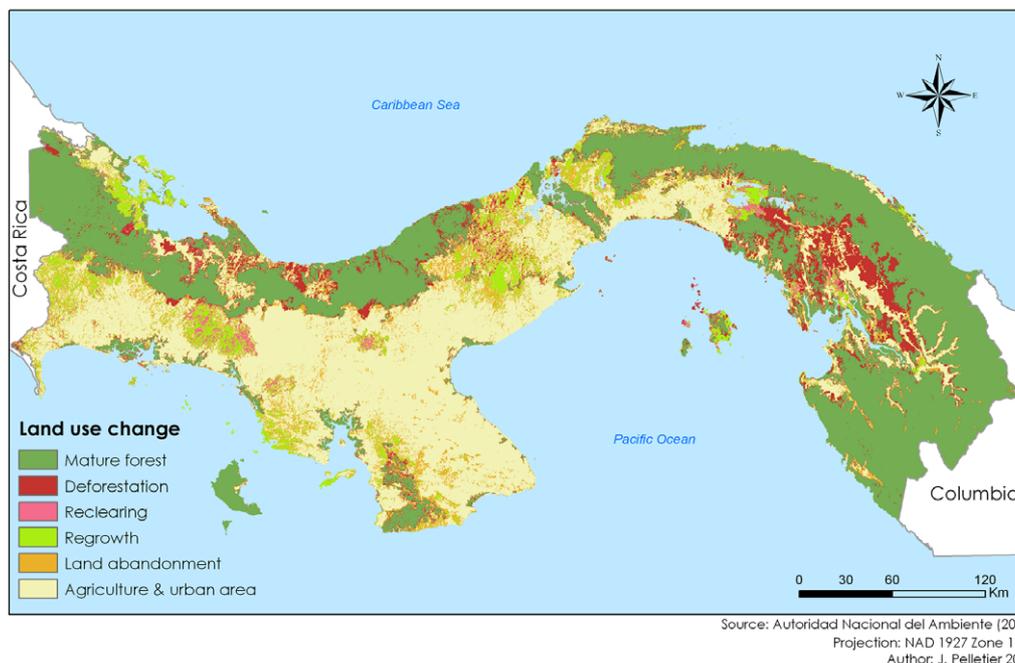


Figure 1. Land-cover change in Panama between 1992 and 2000. Much mature forest clearing occurred in Eastern Panama (Panama and Darién provinces). Secondary forest regrowth, plantations, and fallow land are mainly in Central Panama (Panama Canal watershed) and in Western Panama (Chiriquí, Bocas del Toro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

(SI) at stacks.iop.org/ERL/6/024005/mmedia). The first-order Markov model was used to determine the land-use dynamics after deforestation. The book-keeping 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. 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 in the SI (available at stacks.iop.org/ERL/6/024005/mmedia). 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 the SI available at stacks.iop.org/ERL/6/024005/mmedia). 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 the SI (available at stacks.iop.org/ERL/6/024005/mmedia). 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 CO₂ emissions from soils and forest degradation, as well as emissions of non-CO₂ 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.

Table 1. Satellite images used for the creation of the land-cover maps of 1992 and 2000 for Panama. (Note: 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.)

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

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 the SI (available at stacks.iop.org/ERL/6/024005/mmedia). 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 (Hammonds *et al* 1994, Granger Morgan and Henrion 1990).

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 the SI available

at stacks.iop.org/ERL/6/024005/mmedia). 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).

3. Results

3.1. Sensitivity analysis

3.1.1. 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 1 yr 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 10 yr period rather than an 8 yr period. Since the time interval between two images of the same area is generally greater than eight years, a 10 yr

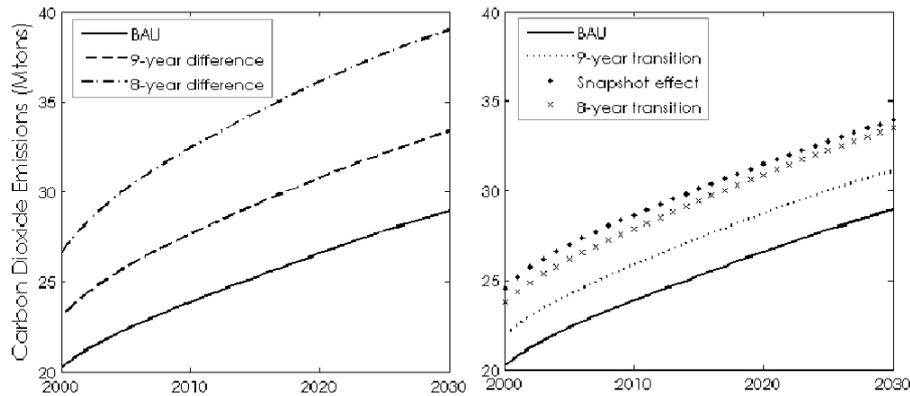


Figure 2. Sensitivity of emissions to errors in land-cover maps (uncertain timespan and snapshot effect). For the REL, ten years of difference between the two land-cover maps (1990 and 2000) is considered. The left pane shows the effect of assuming a 9 yr interval between the two land-cover maps produces 15.6% higher emissions, and an 8 yr 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 yr and an 8 yr 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.

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 yr and 8 yr 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 (CV) 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).

3.1.2. 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 5 yr period all fallow land existing at the beginning of the time period should have returned to agriculture. For our 10 yr 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.

3.1.3. Carbon stock data. Fallow land covers a significant portion of Panama, but it is relatively understudied in terms

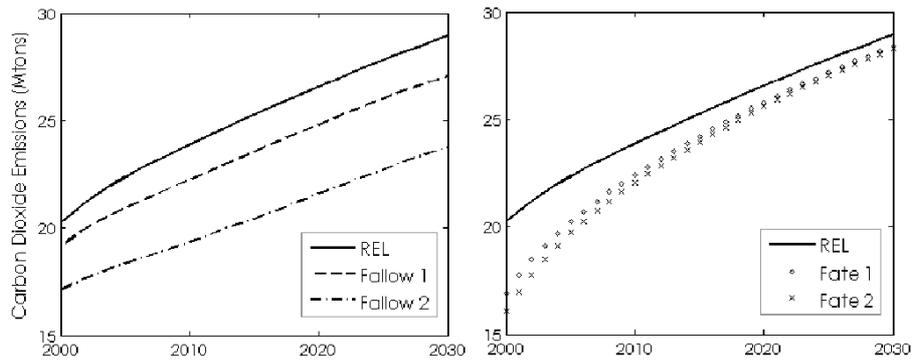


Figure 3. Results of the sensitivity analysis performed on the carbon value found in the fallow land-cover (left; REL = χ , fallow 1 = $\chi-10$, fallow 2 = $\chi/2$) and on parameters linked to the fate of carbon after deforestation (right; REL ($f_{\text{burn}} = 0.6$; $f_{\text{slash}} = 0.339$; $f_{\text{prod}}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

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 3, left).

For mature forest carbon stocks, we used the various forest inventory carbon stock estimates gathered for the Forest Resources Assessment (2005) of Panama (SI available at stacks.iop.org/ERL/6/024005/mmedia). 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.

3.1.4. 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 3(b)). This result might be different if other non-CO₂ greenhouse gases (e.g. CH₄, NO₂) were accounted for.

3.2. 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 (SI available at stacks.iop.org/ERL/6/024005/mmedia). 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 (plot size and number of data points), and random error (lack of representativeness) 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 CO₂ emissions from land-cover change for the entire country, the overall model output uncertainty reaches an average of $\pm 43.5\%$ between the 95% confidence intervals and the mean generated from the Monte Carlo simulations.

3.3. 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

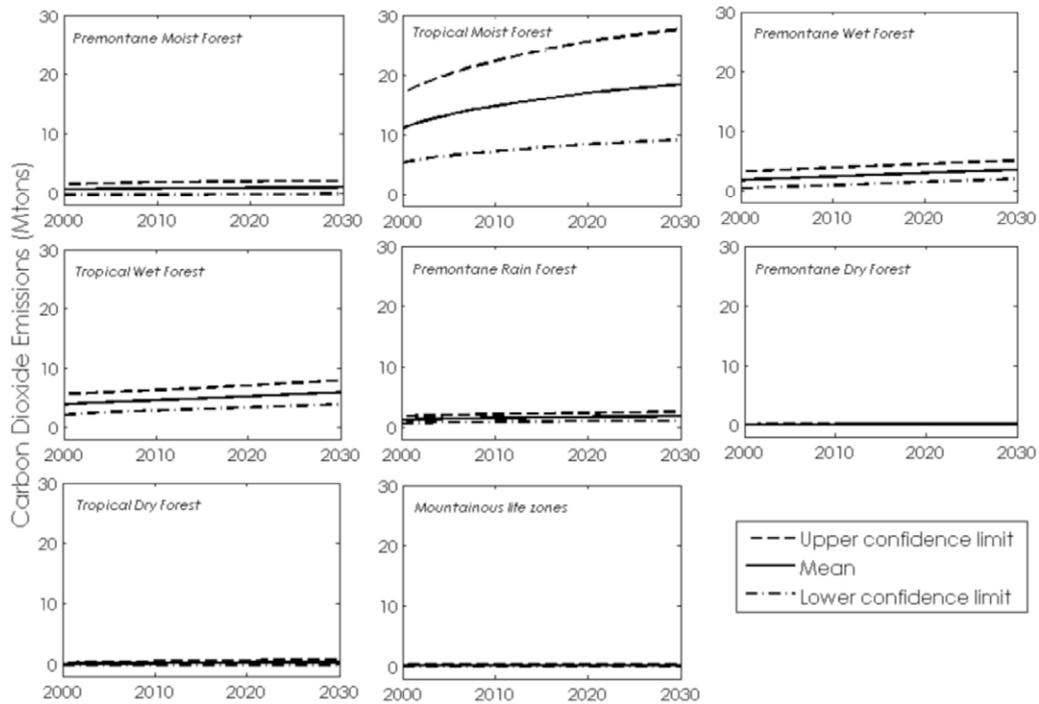


Figure 4. Mean emissions and confidence bounds (95% confidence intervals) of CO₂ emissions obtained from Monte Carlo simulation with 10 000 iterations to propagate the errors coming from input variables of the model per life zone. Moist Tropical forest, Premontane Wet forest and, Tropical Wet forest are the life zones with the greatest uncertainty.

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.

3.4. Combining scenarios and uncertainty

The most striking result from this analysis is that when comparing the five scenarios with the confidence bounds analysed 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+.

4. 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 *et al* 2001, Houghton 2005) and hamper accurate emission estimates (Houghton *et al* 2000). The combination of errors drawn from allometric equations and sampling can be as large as 20–50% of the aboveground biomass estimate (Chave *et al* 2004, Keller *et al* 2001, Persson and Azar 2007).

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

Reference emission level (REL)	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Using the same spatial area covered by the CBMAP II project, this scenario included: <ol style="list-style-type: none"> (1) the Palo Seco Forest Reserve, the protected area included in CBMAP II project with the highest deforestation, (2) the Darien bio-geographic region of Panama, where most mature forest clearing between 1990 and 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	<ul style="list-style-type: none"> • It includes 54 protected areas under different management categories and covers 2359 215 ha^a • 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	<ul style="list-style-type: none"> • 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^{b,c}. 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^{d,e} • Ten 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 ten villages. • This scenario assumes that 100% of the deforestation is curbed.
Stern review	<ul style="list-style-type: none"> • 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^f, and is used as the upper limit for deforestation reduction. • It includes a progressive implementation over ten years.

^a 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.

^b Tschakert *et al* (2007). ^c Sloan (2008). ^d Contraloría General de la República (2001a).

^e Contraloría General de la República (2001b). ^f Stern (2006).

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 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

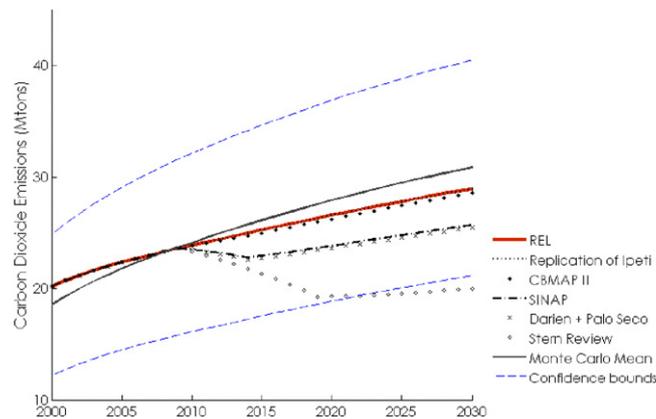


Figure 5. Comparison of the REL and five different scenarios to reduce emissions from deforestation in Panama with the confidence bounds (95% confidence intervals) and the mean obtained from the Monte Carlo uncertainty analysis. The red line represents the reference emission level, which is much closer 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.

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 Ipeti-Emberá (10)	235.2	0.7	0.02
CBMAP II	747.4	2.2	0.30
SINAP	5 965.9	17.4	2.48
Palo + Darien	6 443.4	18.7	2.66
Stern review	17 184.7	50	6.03

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.

4.1. 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

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	2.2–19.1	-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)	15.6–35.2	-Map based on a mosaic of satellite images from very different years -Low availability of useable 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

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* 2008, 2007). 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 yr 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 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 8–10 yr time intervals could significantly reduce uncertainties on land-cover and forest change processes (DeFries *et al* 2007, GOF-C-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, 2004b, Souza *et al* 2005a, 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 regrowth 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 modelling 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 CO₂ emissions reduced, high uncertainties around emission reduction estimates would not be to the country's benefit.

4.2. 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+ in 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* (Panamá, República de Panamá: Autoridad Nacional del Ambiente)
- ANAM 2006 *Indicadores Ambientales de la República de Panamá* (Panamá, República de Panamá: Autoridad Nacional del Ambiente)
- ANAM/ITTO 2003 *Informe final de resultados de la cobertura boscosa y uso del suelo de la República de Panamá: 1992-2000* (Panamá, República de Panamá: Autoridad Nacional del Ambiente)
- Angelsen A 2008 REDD models and baselines *Int. Forest. Rev.* **10** 465–75
- Angelsen A, Brown S, Loisel C, Peskett L, Streck C and Zarin D 2009 *Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report* (Washington, DC: Meridian Institute)
- Asner G P 2009 Tropical forest carbon assessment: integrating satellite and airborne mapping approaches *Environ. Res. Lett.* **4** 034009
- Asner G P, Keller M, Pereira R, Zweede J C and Silva J N M 2004a Canopy damage and recovery after selective logging in Amazonia: field and satellite studies *Ecol. Appl.* **14** S280–98
- Asner G P, Keller M and Silva J N M 2004b Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon *Glob. Change Biol.* **10** 765–83
- Asner G P *et al* 2010 High-resolution forest carbon stocks and emissions in the Amazon *Proc. Natl Acad. Sci. USA* **107** 16738–42
- Bellassen V and Gitz V 2008 Reducing emissions from deforestation and degradation in Cameroon—assessing costs and benefits *Ecol. Econom.* **68** 336–44
- Bottcher H, Freibauer A, Obersteiner M and Schulze E D 2008 Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model *Ecol. Modell.* **213** 45–62
- Caspersen J P, Pacala S W, Jenkins J C, Hurtt G C, Moorcroft P R and Birdsey R A 2000 Contributions of land-use history to carbon accumulation in US forests *Science* **290** 1148–51
- Chave J, Condit R, Aguilar S, Hernandez A, Lao S and Perez R 2004 Error propagation and scaling for tropical forest biomass estimates *Phil. Trans. R. Soc. B* **359** 409–20
- Chomitz K M 2007 *At Loggerheads?: Agricultural Expansion, Poverty Reduction, and Environment in the Tropical Forests* (Washington, DC: The International Bank for Reconstruction and Development/The World Bank)
- Condit R *et al* 2001 The status of the Panama Canal watershed and its biodiversity at the beginning of the 21st century *Bioscience* **51** 389–98
- Contraloría General de la República 2001a *VI Censo Agropecuario. Dirección de Estadística y Censo* (República de Panamá)
- Contraloría General de la República 2001b *Censo Población y Viviendas 2000. Dirección de Estadística y Censo* (República de Panamá)
- Defries R, Achard F, Brown S, Herold M, Murdiyarso D, Schlamadinger B and De Souza C 2007 Earth observations for estimating greenhouse gas emissions from deforestation in developing countries *Environ. Sci. Policy* **10** 385–94
- Ebeling J and Yasue M 2008 Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits *Phil. Trans. R. Soc. B* **363** 1917–24
- FAO 2006 *Forest Resource Assessment* (Rome: Food and Agriculture Organization)
- FCPF 2010 *General Overview: Forest Carbon Partnership Facility* (Washington, DC: World Bank)
- Fearnside P M 1997 Greenhouse gases from deforestation in Brazilian Amazonia: Net committed emissions *Clim. Change* **35** 321–60
- 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 *Clim. Change* **46** 115–58
- Fearnside P M 2001 Saving tropical forests as a global warming countermeasure: an issue that divides the environmental movement *Ecol. Econ.* **39** 167–84
- Foody G M 2002 Status of land cover classification accuracy assessment *Remote Sens. Environ.* **80** 185–201
- Foody G M 2009 The impact of imperfect ground reference data on the accuracy of land cover change estimation *Int. J. Remote Sens.* **30** 3275–81

- FRA 2010 *Global Forest Resources Assessment 2010: Main Report* (Rome: Food and Agriculture Organization of the United Nations)
- 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* (Alberta, Canada: GOFC-GOLD Project Office, Natural Resources Canada)
- Granger Morgan M and Henrion M 1990 *Uncertainty, A guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis* (New York: Cambridge University Press)
- Grassi G, Monni S, Federici S, Achard F and Mollicone D 2008 Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates *Environ. Res. Lett.* **3** 035005
- Gullison R E et al 2007 Tropical forest and climate policy *Science* **316** 985–6
- Gutierrez R 1999 Inventario Nacional de Gases de Efecto Invernadero para el modulo *Cambio de Uso de la Tierra y Silvicultura* ed ANAM (Panamá: República de Panamá)
- Gutierrez R 2005 *Forest Resource Assessment 2005: Country Report Panama* (Rome: Food and Agriculture Organization-Forest Department)
- Hall A 2008 Better RED than dead: paying the people for environmental services in Amazonia *Phil. Trans. R. Soc. B* **363** 1925–32
- Hammonds J S, Hoffman F O and Bartell S M 1994 *An Introductory Guide to Uncertainty Analysis in Environmental and Health Risk Assessment* ed O A K Senes and I Ridge (Oak Ridge, TN: Oak Ridge National Laboratory)
- Heckadon-Moreno S and McKay A (ed) 1984 *Colonización y Destrucción de Bosques en Panamá: Ensayos sobre un grave Problema ecológico* (República de Panamá: Asociación Panameña de Antropología)
- 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)
- 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 B* **55** 378–90
- Houghton R A 2005 Aboveground forest biomass and the global carbon balance *Glob. Change Biol.* **11** 945–58
- Houghton R A 2010 How well do we know the flux of CO₂ from land-use change? *Tellus B* **62** 337–51
- Houghton R A, Lawrence K T, Hackler J L and Brown S 2001 The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates *Glob. Change Biol.* **7** 731–46
- Houghton R A, Skole D L, Nobre C A, Hackler J L, Lawrence K T and Chomentowski W H 2000 Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon *Nature* **403** 301–4
- IPCC 2000 Good practice guidance and uncertainty management in national greenhouse gas inventories (Hayana, Japan: IPCC/OECD/IEA/IGES)
- Karsenty A 2008 The architecture of proposed REDD schemes after Bali: facing critical choice *Int. Forest. Rev.* **10** 443–57
- Kauffman J B, Hugues R F and Heider C 2009 Carbon pool and biomass dynamics associated with deforestation, land use, and agricultural abandonment in the neotropics *Ecol. Appl.* **19** 1211–22
- Keller M, Palace M and Hurr G 2001 Biomass estimation in the Tapajos National Forest, Brazil: examination of sampling and allometric uncertainties *Forest Ecol. Manag.* **154** 371–82
- Laurance W F 2007 A new initiative to use carbon trading for tropical forest conservation *Biotropica* **39** 20–4
- Monni S, Peltoniemi M, Palosuo T, Lehtonen A, Makipaa R and Savolainen I 2007 Uncertainty of forest carbon stock changes—implications to the total uncertainty of GHG inventory of Finland *Clim. Change* **81** 391–413
- Myers N, Mittermeier R A, Mittermeier C G, Da Fonseca G A B and Kent J 2000 Biodiversity hotspots for conservation priorities *Nature* **403** 853–8
- Nahorski Z and Jeda W 2007 Processing national CO₂ inventory emissions data and their total uncertainty estimates *Water, Air, Soil Pollution: Focus* **7** 513–27
- Nogueira E M, Fearnside P M, Nelson B W and 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 Ecol. Manag.* **248** 119–35
- Nogueira E M, Nelson B W, Fearnside P M, Franca M B and 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 Ecol. Manag.* **255** 2963–72
- Oestreicher J S et al 2009 Avoiding deforestation in Panamanian protected areas: an analysis of protection effectiveness and implications for reducing emissions from deforestation and forest degradation *Glob. Environ. Change* **19** 279–91
- Olander L P, Gibbs H K, Steininger M, Swenson J J and Murray B C 2008 Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods *Environ. Res. Lett.* **3** 025011
- Peltoniemi M, Palosuo T, Monni S and Makipaa R 2006 Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation *Forest Ecol. Manag.* **232** 75–85
- Persson U M and Azar C 2007 Tropical deforestation in a future international climate policy regime—lessons from the Brazilian Amazon *Mitigat. Adapt. Strategies Glob. Change* **12** 1277–304
- Ramankutty N, Gibbs H K, Achard F, Defries R, Foley J A and Houghton R A 2007 Challenges to estimating carbon emissions from deforestation *Glob. Change Biol.* **13** 51–66
- Rypdal K and Winiwarter W 2001 Uncertainties in greenhouse gas emission inventories—evaluation, comparability and implications *Environ. Sci. Policy* **4** 107–16
- Sloan S 2008 Global environmental change-human and policy dimensions *Glob. Environ. Change* **18** 425–41
- Smith J E and Heath L S 2001 Identifying influences on model uncertainty: an application using a forest carbon budget model *Environ. Manag.* **27** 253–67
- Souza C M Jr, Roberts D A and Cochrane M A 2005a Combining spectral and spatial information to map canopy damage from selective logging and forest fires *Remote Sens. Environ.* **98** 329–43
- Souza C M Jr, Roberts D A and Monteiro A 2005b Multitemporal analysis of degraded forests in the Southern Brazilian Amazon *Earth Interact.* **9** 1–25
- Stern N 2007 *The Economics of Climate Change: The Stern Review* (Cambridge: Cambridge University Press)
- Tschakert P, Coomes O T and Potvin C 2007 *Ecol. Econom.* **60** 807–20
- 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) Project Appraisal Document to the Republic of Panama* ed C A C M UNIT (Washington, DC: World Bank)