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Johanne Pelletier, Jonah Busch & Catherine Potvin

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Abstract Uncertainty in emissions and emission changes estimates constitutes an unresolved issue for a future international climate agreement. Uncertainty can be addressed 'upstream' through improvements in the technologies or techniques used to measure, report, and verify (MRV) emission reductions, or 'downstream' through the application of discount factors to more uncertain reductions. In the context of Reducing Emissions from Deforestation and forest Degradation (REDD+), we look at the effects of upstream interventions on reductions in uncertainty, using data from Panama. We also test five downstream proposals for discounting uncertainty of the potential credits received for reducing emissions. We compare the potential compensation received for these emission reductions to the cost of alternative upstream investments in forest monitoring capabilities. First, we find that upstream improvements can noticeably reduce the overall uncertainty in emission reductions. Furthermore, the costs of upstream investments in improved forest monitoring are relatively low compared to the potential benefits from carbon payments; they would allow the country to receive higher financial compensation from more certain emission reductions. When uncertainty is discounted downstream, we find that the degree of conservativeness applied downstream has a major influence on both overall creditable emission reductions and on incentives for upstream forest monitoring improvements. Of the five downstream approaches that we analyze, only the Conservativeness Approach and the Risk Charge Approach provided consistent financial incentives to reduce uncertainty upstream. We recommend specifying

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J. Pelletier (✉)
Woods Hole Research Center, 149 Woods Hole Rd, Falmouth, MA 02540-1644, USA
e-mail: jpelletier@whrc.org

J. Busch
Center for Global Development, 2055 L Street NW, Fifth Floor, Washington, DC 20036, USA

C. Potvin
Department of Biology, McGill University, Montreal, QC, Canada H3A 1B1

C. Potvin
Smithsonian Tropical Research Institute, Roosevelt Ave., Ciudad de Panamá 0843-03092, República de Panamá

the use of one of these two approaches if REDD+ emission reductions are to be traded for emission reductions from other sectors.

1 Introduction

Uncertainties around the estimation of greenhouse gas (GHG) emissions and removals merit consideration in the context of carbon accounting and trading under the United Nations Framework Convention on Climate Change (UNFCCC). Uncertainty in GHG estimates can hinder the fulfillment of the first objective of the Convention on Climate Change to "stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". First, uncertainty in GHG estimates can prevent the international community from assessing how different countries are meeting their pledged emission reduction targets. Compliance is especially difficult to assess, and likely to be controversial, when uncertainty is equal to or greater than pledged emission reductions. Under the Kyoto Protocol (KP), the agreed emission changes for most countries are of the same order of magnitude as the uncertainty that underlies their emissions estimates (Jonas et al. 2011). This has led some authors to question the 'make or break' of compliance with emission reduction targets when factoring in the uncertainty (Bartoszczuk and Horabik 2007; Jonas et al. 2010a; Lieberman et al. 2007; Nahorski et al. 2007). Second, uncertainty threatens the environmental integrity of carbon trading systems. Under a carbon market, care would have to be taken to ensure that uncertainties around both emissions estimates and purchased offsets do not result in more certain emissions being traded for less certain emission reductions, thereby reducing certainty that overall climate targets have been met (Box 1, SI). The benefits of carbon markets largely depend on reliable estimation of uncertainties in both emissions and offsets and on a credible mechanism to deal with these uncertainties.

Uncertainty is an important consideration in the context of Reducing Emissions from Deforestation and forest Degradation (REDD+) since 1) the land-use/cover change and forestry is the sector identified as having the largest uncertainties (Canadell et al. 2010; Le Quéré et al. 2009), 2) many developing countries still lack capabilities for estimating stocks and flows from forests (Romijn et al. 2012), 3) the financial mechanism planned for compensating developing countries in their successful efforts to slow, halt or revert forest cover change could include the use of offsets (UNFCCC 2010). The integration of REDD+ in the climate regime is providing a new impetus to deal with uncertainty as the offsetting of more certain emissions from fossil fuel with uncertain emission reductions (ERs) from deforestation remains an open question with possibly large consequences.

One possible avenue is to reduce uncertainties prior to carbon accounting, through 'upstream' investments in improved monitoring technologies and techniques. The UNFCCC specifies a step-wise approach to monitoring improvements in the REDD+ context (UNFCCC 2010). A growing body of literature has been produced on ways to improve capabilities of developing countries for estimating forest-based emissions and removals, e.g., (GFOI 2013; GOFC-GOLD 2012; Hewson et al. 2013). Important efforts are underway to improve data availability and accuracy in developing countries involved in the Forest Carbon Partnership Facility (FCPF) and the United Nations—REDD Program. Participating countries are receiving significant technical and financial support to advance the development of their forest monitoring systems and improve the quantification of carbon emissions and removals from forests. These efforts will most likely result in important reductions in the error associated with estimating carbon stock changes from forests over time.

Another approach to deal with uncertainties is to limit or discount them through 'downstream' measures. By discounting uncertainty, we refer to the use of an adjustment or crediting rules used *a posteriori* of the carbon accounting that would reduce the risk of overestimating emission reductions or removals. At present, there are no internationally accepted guidelines regulating uncertainty following carbon accounting. Parties to the UNFCCC are encouraged, but not obliged, to report on uncertainty in their national GHG inventory (IPCC 2003, 2006; Jonas et al. 2010b). Under KP, GHG inventory uncertainty is monitored, so countries that have emission reduction commitments are requested to report on uncertainty levels (Jonas et al. 2010a, b), but it is not regulated, which means that there are no rules to limit or discount for uncertainty when evaluating compliance. In carbon trading, the UNFCCC does not provide compulsory instructions on how uncertainty must be addressed within finance mechanisms, and uncertainty is generally ignored (Marland et al. 2009).

Several approaches and proposals have been put forth to discount for uncertainty in accounting, under REDD+ or other contexts. First, under the KP, there are rules to apply adjustments when GHG inventory data are found to be incomplete and/or are prepared in a way that is not consistent with the adopted International Panel on Climate Change (IPCC) guidelines (UNFCCC 2003, 2005). These adjustments apply different factors according to different fixed uncertainty ranges; more stringent correction is imposed with higher levels of uncertainty.

Then, under the KP Clean Development Mechanism (CDM) framework, a draft proposal on how to deal with uncertainties in ER calculations is provided (CDM Methodologies Panel 2008). The Verified Carbon Standard (VCS) in its standards requires applying deductions for uncertainty by using conservative factors specified in this CDM draft proposal (CDM Methodologies Panel 2008; VCS 2013). Under the CDM framework, however, discussions have been going on about accounting for uncertainty of measurement through the use of adjustments to ensure that ERs are determined conservatively and consistently across project types and methodologies, but no formal decision has been adopted to date (CDM Methodologies Panel 2008; UNFCCC 2012). Different methodologies are currently used in different project sectors for the purpose of addressing the uncertainty in measurements.

Carbon trading ratios have been proposed to discount for uncertainty in carbon trading systems (Gillenwater et al. 2007). The uncertainty levels would be used to set the value of emission allowances from two different sources by establishing the number of units of emissions from one source that is equivalent to or offset by one unit of emissions allowances purchased from another source (Gillenwater et al. 2007).

Another proposal, coined the Conservativeness Approach, was developed by Grassi et al. (2008), to conservatively estimate ER, thus increasing their credibility. Two main methods were proposed: the Reliable Minimum Estimate (RME) and the trend uncertainty of ER estimates (Grassi et al. 2008, 2013). The RME compares the difference between the lower limit of the confidence interval of the first time period (or reference period) and the higher limit of the confidence interval for the second period. This first method was deemed too draconian for the REDD+ context because it would not generate any credits for developing countries unless major reduction in deforestation is achieved (Grassi et al. 2013; Pelletier et al. 2013; Plugge et al. 2013). The second method uses the lower confidence bound of the trend uncertainty, that is, the uncertainty of the difference of net emissions over time.

The FCPF Carbon fund adopted a procedure that requires setting aside an amount of emission reductions reflecting their associated level of uncertainty at 90 % confidence intervals (CI) in a buffer reserve. The amount set aside in this reserve is determined by using conservative factors applied according to different uncertainty bands on these emission reductions (FCPF 2013).

Finally, another recent proposal to deal with uncertainty is derived from the actuarial science for insurance risk assessment (Marland et al. 2014), hereafter called the Risk Charge Approach. Under this approach, it is suggested applying added margin value to the price of carbon emissions based on the uncertainty levels obtained from the confidence intervals, at the 95 % confidence intervals or any other confidence levels.

Up until now, upstream interventions and downstream proposals to deal with uncertainty have not yet been quantitatively compared in the REDD+ context. In this paper, we compare: 1) the cost and benefit ratio of alternative upstream investments; 2) the crediting implications of alternative downstream measures; and 3) the implications of alternative downstream measures for incentivizing investments in upstream interventions. Using data from Panama, we look at the impact of upstream forest monitoring improvement in remotely sensed land-cover change assessment, in forest carbon density measurement, and in their product and quantify the effect of those improvements on the overall uncertainty in ERs from deforestation and forest degradation. We test five downstream approaches or proposals on the potential credits obtained from emission reductions: 1) the KP Conservativeness Factors; 2) the CDM Draft Proposal; 3) the Conservativeness Approach; 4) the FCPF Carbon Fund Approach; 5) the Risk Charge Approach. Since upstream and downstream approaches are not mutually exclusive; we consider them separately and in combination to understand their full value. Then, we assess the potential compensation received for these emission reductions to the costs involved in improving forest monitoring capabilities. Finally, we examine how the distinct crediting rules that are proposed for addressing uncertainty downstream will affect a country's interest to invest in forest monitoring systems to reduce uncertainty upstream.

2 Methods

2.1 Emission changes and calculation of error from deforestation and forest degradation

We compared emissions from two time periods that were marked by a decrease in deforestation and forest degradation for Panama, 1992–2000 as reference period and 2000–2008 as assessment period (Fig. 1). Three land-cover maps obtained from the Panamanian government were used to determine the area of land-cover change for 1992 and 2000 (ANAM/ITTO 2003) and for 2008 (CATHALAC 2009). Emission factors were obtained from the Food and Agricultural Organization's Forest Resources Assessment country report (2005 and 2010) (Gutierrez 2010) and IPCC default value when data was unavailable. More information on emission calculation is provided in supplementary information (SI).

We evaluated the overall uncertainty on emission reductions using Monte Carlo probabilistic uncertainty propagation, as suggested by IPCC. Emission reductions were calculated using the uncertainty of the trend, that is, the uncertainty of the difference in emissions between the first (1992–2000) and second (2000–2008) periods. Activity data (AD) was considered to be uncorrelated between periods while emission factors (EF) were fully correlated between periods (Hiraishi et al. 2006). We made a distinction in ERs from deforestation and from forest degradation because they differ in terms of associated error. The calculation of error was carried out for each forest monitoring improvement sensitivity scenarios described below.

2.2 Upstream forest monitoring improvement and investments scenarios

Fifteen sensitivity scenarios of key improvements in forest monitoring were formulated to test the impact of reducing uncertainty upstream of emission change accounting. These fifteen

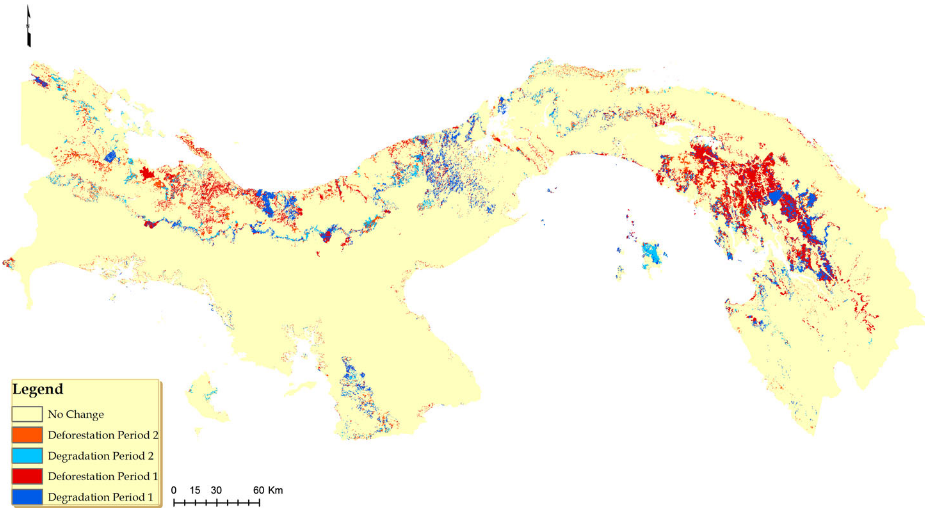


Fig. 1 Map of deforestation and forest degradation in Panama for the 1992–2000 and 2000–2008 periods (Author: Pelletier, J.; Data source: ANAM/ITTO (2003) and CATHALAC (2009)

upstream improvement scenarios were then compared using the Coefficient of Variation (CV) of the Standard Deviation (SD) relative to the mean ERs obtained from Monte Carlo simulations.

These fifteen sensitivity scenarios simulate improvements to land-cover change maps based on remote sensing (activity data), forest carbon stock data (emission factor) or both. For activity data, the sensitivity scenarios were performed to take into account some characteristics of the land-cover map products and published accuracy levels. The tests were developed to compensate for the lack of quantitative classification accuracy assessment for each land-cover map, as well as for the land area change. The reports accompanying those maps qualify them as having 'very high classification accuracy' but does not provide a quantitative evaluation for each map, neither the change nor adjusted estimate after correction of classification error. We utilized two main components linked to land-cover map quality: 1) the margin of error around the area change estimate, using different levels of quality that reflect estimates as described in Olofsson et al. (2013) and 2) the time intervals between images composing the maps for each time period t_1 and t_2 as discussed in Pelletier et al. (2011), which affect the amount of annual emissions estimated for the period (SI, Table I+text). For the sensitivity tests on emission factor, we used information provided by Chave et al. (2004) for the Panama Canal watershed to parameterize the scenarios. The authors distinguish between four main types of error in forest aboveground biomass including: 1) quality of the data or tree-level error due to measurement discrepancy (for Diameter at Breast Height (DBH), tree height and wood specific gravity); 2) the choice of allometric model or the quality of the model; 3) the size of the sampled area or within-plot uncertainty and 4) representativity of the plots or the among-plot uncertainty. This information allowed us to use empirically-based levels of error in above-ground biomass estimates (AGB) (% error associated with each component expressed as standard error of mean (s.e.m.)) and build scenarios testing for improvements in each of the four types of error on above ground biomass (Table I, SI).

Out of these 15 upstream error improvement scenarios, we determined the direct investment costs in forest monitoring capabilities of the four most contrasting scenarios thanks to the input provided by the National Environmental Authority of Panama (ANAM) and the Food and Agriculture Organization (FAO) involved in the UN-REDD program in Panama. These four upstream scenarios are: 1) No error reduction (S1); 2) Error reduction in remote sensing (RS) mapping products (S2); 3) Error reduction in forest carbon density (FCD) (S3); 4) Error reduction in both RS and FCD (S4). We gathered the costs associated with the production of existing maps and those of potential improved land-cover maps. We estimated the costs of error reduction in forest carbon density based on experts' opinion using per plot-cost evaluation from the sampling design elaborated by the FAO for the national forest inventory (Table V, SI). For this analysis, we assume that investing in forest monitoring capabilities leads to certain quantifiable reductions in error. We acknowledge that some investments in MRV might not lead to a reduction of the error or that some investments may lead to error reduction that is hardly quantifiable (e.g., capacity-building of technicians).

2.3 Comparison of five downstream measures

We tested five approaches proposed to discount for uncertainty downstream of accounting, by using the four most contrasting forest monitoring improvement scenarios described above. The five downstream schemes evaluated were: 1) the KP Conservativeness Factors where a discount factor reflects the 25^{th} or 75^{th} percentile of the uncertainty range associated with the estimate, applying it with and without the trend uncertainty; 2) the CDM Draft Proposal with conservative adjustments which were applied if the overall random uncertainty was superior to a threshold of 15 % (at a 95 % confidence level); 3) the Conservativeness Approach where the lower confidence bound of the trend uncertainty was employed under the 5, 15 and 25 % percentiles as different tested levels to receive compensation; 4) the FCPF Carbon Fund Approach that requires setting aside an amount of ERs reflecting their associated level of uncertainty at 90 % confidence intervals (CI) in a buffer reserve; and 5) the Risk Charge Approach where the value of uncertainty is calculated as a risk charge and a fee is added to the basic costs of carbon emissions, using the 95, 85 and 75 % percentiles tested. More details and adjustment factor tables are available in supplementary information.

Finally, we estimated the potential amount of credits received after applying the downstream measures proposed in the five approaches. For the four upstream error reduction scenarios, we compared the investment costs estimated for the forest monitoring improvement scenarios with the potential payment received for discounted emission reductions. We used a value of $10 per ton of CO_2 equivalent (CO_2e) for emission reductions to evaluate these potential credits.

3 Results

3.1 Reducing error upstream

The fifteen upstream forest monitoring improvement scenarios generated display important differences in terms of associated uncertainty, ranging from 10.6 to 65.6 % in their CV (Table 1). The lowest value (10.6 %) is obtained under a simulation assuming no error in land area change estimates and no error in forest carbon density (FCD) estimates, so accounting only for error in carbon for degraded forest and other land uses. The highest value (65.6 %), which would bear the characteristics of the information currently available for Panama prior to the national forest inventory and new land-cover mapping efforts, assumes no reduction of error in remote sensing assessment (RS) and in forest carbon density estimates (Scenario 1, S1).

Table 1 Mean annual emission reductions, standard deviation and coefficient of variation obtained for fifteen upstream improvement sensitivity scenarios simulated using Monte Carlo uncertainty propagation. The columns for Activity data and Emission factor describe the parameters adopted for each sensitivity scenario

Scenarios	Activity data							Emission Factor				Mean annual ER (in Mtons of CO2)	Standard deviation (in Mtons of CO2)	Coefficient of variation[3] (in %)
	Area change accuracy[1]				Time interval[2] (in yrs)			No error	Low	Average	High			
	0%	15%	25%	50%	0	1	2	0%	11%	26%	58%			
1	■				■			■				11.9	1.3	10.6
2	■				■				■			11.9	2.1	17.4
3	■					↔			■			13.9	2.5	17.9
4	■				■					■		11.8	3.2	26.8
5		■					■	■				11.9	1.4	12.1
6			■				■	■				11.9	1.7	14.4
7			■				■		■			11.9	2.4	20.0
8			■		■					■		13.9	4.1	29.7
9		■				↔				■		13.1	3.9	29.5
10			■				■			■		11.9	3.4	28.8
11				■		↔		■				13.4	3.6	26.5
S1				■		↔					■	13.4	8.8	65.6
S2		■					■				■	11.8	6.7	56.9
S3				■		↔			■			13.4	4.1	30.4
S4		■					■		■			11.9	2.2	18.4

[1] The accuracy of the land area change estimates was simulated using the margins of error around the change area estimates. The margins of error represent different levels of confidence around the estimate. In Table 1, the percentage indicated defines the spread of margins of error within which we sampled during our Monte Carlo simulations. For example, if the change area estimate is 100 ha and the accuracy of the land area change is 25 %, the range in which we sample is between 75 and 125 ha

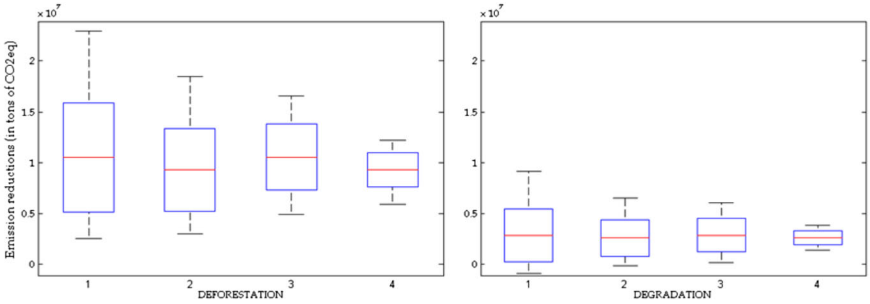
[2] As described in Pelletier et al. (2011), the images composing each land-cover maps are from different years. So, the change map obtained for a period has areas separated by different time intervals, which affect the amount of emission and ER for a given time. The ↔ symbol indicates that in the scenario we sampled between this intervals during the Monte Carlo simulations

[3] The Coefficient of Variation (CV) is calculated as the Standard Deviation (SD) on the mean ER obtained from Monte Carlo simulations, expressed in percentage. This CV gives a measure of the share of the ER that is affected by error and provides a comparison measure of the impact of upstream improvements in reducing uncertainty

The largest reduction in uncertainty results from upstream improvements in FCD which is equivalent to 35.0 % error reduction when comparing scenarios with high to low error in FCD. Improvements in land area change estimates would lead to a reduction of 8.5 % of the overall random error. However, improvement on activity data affects the quantity of emissions and ER with the difference of 12.1 % or 1.53 M tons of CO_2e in mean annual emission reductions with and without RS upstream improvement. The change on the mean emission reductions estimated between scenarios show the effect of both the accuracy of land area change estimates and the time intervals between land-cover assessment (e.g., Table 1, scenario 8, 9, 10).

The lowest reachable level of uncertainty is estimated at 18.4 % (C.V.) for Panama and is obtained when error is reduced in both RS and FCD (Scenario 4, S4). This threshold is indicative of the variability of the components being measured and used to estimate emissions and ER from deforestation and forest degradation. Although the fifteen scenarios presented in Table 1 are based on theoretical reduction of error obtained with the input of different studies, they provide a general appreciation of the levels of uncertainty in emission reductions that can be expected.

Changes in uncertainty are the most extreme between S1 without error reduction and S4 where error is reduced in both RS and FCD (Fig. 2). Based on the comparison of the 1992–2000 and 2000–2008 period, curbed forest degradation represents 17.3 % of the total ER for S4, representing a significant share of the reduction in emissions. The associated uncertainty to emission reductions from reduced forest degradation is higher than for reduced deforestation, ranging from 29.4 % to



	1= No Error reduction			2=Error reduction in RS			3=Error reduction in FCD			4=Error reduction in RS and FCD		
	Deforestation	Degradation	Overall	Deforestation	Degradation	Overall	Deforestation	Degradation	Overall	Deforestation	Degradation	Overall
5% percentile	2.52	-0.94	2.93	2.99	-0.12	3.40	4.90	0.14	6.87	5.95	1.38	7.97
25% percentile	6.05	0.67	7.46	5.95	1.12	7.25	8.10	1.56	10.54	8.19	2.07	10.46
Mean	10.52	2.87	13.39	9.28	2.59	11.86	10.52	2.87	13.39	9.28	2.59	11.87
75% percentile	13.56	4.28	17.35	11.65	3.64	15.11	12.87	4.03	16.10	10.57	3.09	13.42
95% percentile	22.92	9.14	29.71	18.48	6.53	24.40	16.57	6.07	20.51	12.18	3.87	15.48
CV of SD on emission reductions	63.4%	116.8%	65.6%	53.4%	82.3%	56.9%	32.9%	63.2%	30.4%	19.2%	29.4%	18.4%

Fig. 2 Mean annual emission reductions (in million tons of CO_2e) estimated under the four most contrasting upstream error reduction scenarios with associated 5, 25, 75 and 95 % percentiles and the mean obtained from Monte Carlo analysis. The emission reductions are provided for deforestation, forest degradation, and overall. The coefficient of variation (CV) of the standard deviation on the total ERs is given in percentage terms. We can observe that the distribution for S1 and S2 is slightly asymmetric; this is due to the large error in FCD

116.8 % in CV for these four scenarios compared to 19.2 to 63.4 % in CV for deforestation (Fig. 2). This level of uncertainty for degradation can be explained by the propagation of error over an uncertain mature forest carbon density and in the resulting degraded forest carbon density, compared to more certain carbon estimates for the replacement vegetation after deforestation.

3.2 Comparing the five downstream discounting schemes

The five downstream discounting approaches generated very distinct outcomes in terms of the potential income from selling hypothetical REDD+ offset credits, both across discounting schemes and between the four error reduction scenarios tested. The KP Conservativeness Factors on emissions (Table 2, 1b), the CDM Draft Proposal (Table 2, 2) and the Risk Change Approach at 95 % percentile (Table 2, 5a) are the most restrictive approaches applying the largest deductions for uncertainty. For these three proposals, the grey areas (Table 2) represent cases where no compensation is produced. The most stringent scheme is definitely the KP Conservativeness Factors when applied as stipulated on emissions in the base year and on commitment year, that is, without applying the trend uncertainty. In this case, the discount is the greatest of all the schemes tested with only the upstream scenario with error reduction in both RS and FCD (S4) producing potential credits. The CDM Draft Proposal, because of its upper limit on uncertainty range (Table 2, 2) requires reducing error in FCD to generate credits.

The discounting scheme developed under the FCPF Carbon Fund Approach leads to higher potential credits than the other discounting schemes (Table 2, 4), meaning that less is discounted for the error affecting the estimates. The FCPF Carbon Fund Approach applies conservative factors that discount less than the other schemes and is less stringent by applying them on uncertainty ranges at the 90 % CI (or 90 % percentile in this study).

The potential credits calculated under the KP Conservativeness Factors (Table 2, 1a) are comparable to the CDM Draft Proposal (Table 2, 2). They apply similar deduction, except that the CDM Draft Proposal set a lower threshold below which no deduction is applied (<15 %) and upper limit (>100 %) above which no credit is provided. The potential credits generated would also be similar to what is obtained under the Conservativeness Approach at 25 % percentile (Table 2, 3c) and the Risk Charge Approach at 75 % percentile (Table 2, 5c).

Our results point to a convergence between the Conservativeness and the Risk charge Approaches. The Risk Charge uses the percentage of uncertainty at some determined upper tailed level of confidence while the Conservativeness approach adopts the lower confidence limit. When error is normally distributed, as the distribution is symmetric, both schemes become mathematically equivalent, leading to the same discount and payment. In our case, the S1 and S2 do not have normally distributed error, so the payment evaluated between the two schemes is substantially different. The credits calculated for upstream scenarios S3 and S4 are very similar.

The difference in potential income received between upstream scenarios without reduction of uncertainty (S1) and with reduction of error (S4) is the highest for more stringent downstream discounting approaches. The difference between S1 and S4 is equivalent to 419.6 %, 318.4 % and 92.4 % difference for the Risk charge at 95 % percentile (5a), the KP conservativeness factor without the trend uncertainty (1b) and, the Conservativeness approach at a 5 % percentile (3a) respectively.

Only two schemes generate consistent financial incentive to reduce uncertainty upstream of ER accounting: the Risk charge and the Conservativeness approach. Under the 95 % and 85 % percentile (5a and 5b) for the Risk charge and the 5 % and 15 % percentile (3a and 3b) for the Conservativeness approach, the potential income from selling carbon credits increases as the error is reduced upstream that is, from the no error reduction (S1) to the error reduction in both the RS and FCD scenarios (S4).

Under all other schemes proposed, reducing error does not necessarily lead to higher credits. It is the case for the FCPF Carbon Fund scheme where the discount is smaller and results in no overall incentives in terms of credits generated to reduce error upstream. In effect, the difference between the no error reduction scenario (S1) and the error reduction in RS and FCD (S4) is equal to -3.4 %, which means that fewer credits are generated under S4 compare to S1 (Table 2).

We performed sensitivity tests on the carbon price, using values ranging from \$10 to \$50 per ton of CO_2e. As expected, changing the carbon price changes the amounts produced but the differences underlined between discounting approaches and scenarios remain the same.

When we compare the potential compensation received after applying downstream discounting schemes with the evaluated upstream forest monitoring improvement costs (Table V, SI), we found that the cost of investing in improved forest monitoring constituted only a small fraction of the potential income from REDD+ carbon credits. When reducing error in both RS and FCD, even under the most stringent downstream discounting schemes, the investment costs is equal to only 1.65 % of the potential compensation at \$10/t CO_2e. The exceptions are when no compensation is produced (grey cells, Table 2) or when the trend uncertainty is not used to calculate ERs (Table 2, 1b). In the latter case, forest monitoring investment costs would represent 20.4 % of the total credit obtained for S4.

4 Discussion

Uncertainty in emission reductions from deforestation and forest degradation can be reduced through data collection and by increasing forest monitoring capabilities in developing

Table 2 Comparison of the potential REDD credits for four upstream forest monitoring improvement scenarios (columns) under variations of the five proposed downstream discounting approaches (rows). The column on the right shows the difference in credits obtained between the scenario without error reduction (S1) and with error reduction in both remote sensing assessment and forest carbon density estimates (S4). The two bottom rows of the table show respectively the costs of upstream forest monitoring improvements and the proportion of those costs relative to the most discounted credits (except scheme 1b). Grey areas indicate that no credits are produced

		Upstream forest monitoring improvement scenarios				
		No error reduction (S1)	*Error reduction in RS (S2)*	*Error reduction in FCD (S3)*	*Error reduction in RS and FCD (S4)*	Difference between S1 & S4
Downstream discounting schemes	(1a) **KP conservativeness factor**	$97,759,221	$86,610,344	$109,800,820	$105,622,417	**7.7%**
	(1b) **KP conservativeness factor** on emissions (no trend uncertainty)	-$29,497,135	-$23,628,253	-$16,844,000	$6,737,960	**318.4%**
	(2) **CDM draft proposal**	NA	NA	$111,943,275	$105,978,448	-
	(3a) **Conservativeness approach** at a 5% percentile	$29,349,712	$34,025,389	$68,660,815	$79,708,566	**92.4%**
	(3b) **Conservativeness approach** at a 15% percentile	$56,294,809	$57,121,997	$91,443,135	$96,029,897	**52.2%**
	(3c) **Conservativeness approach** at a 25% percentile	$74,586,528	$72,526,973	$105,364,874	$104,642,212	**33.5%**
	(4) **FCPF Carbon Fund**	$117,846,732	$104,406,990	$123,191,164	$113,929,799	**-3.4%**
	(5a) **Risk charge** at a 95% percentile	-$29,253,906	-$6,716,038	$62,688,344	$82,543,507	**419.6%**
	(5b) **Risk charge** at a 85% percentile	$55,184,718	$56,322,344	$90,804,850	$95,483,330	**53.5%**
	(5c) **Risk charge** at a 75% percentile	$94,330,303	$86,201,296	$106,821,438	$103,168,710	**9.0%**
	Upstream improvement costs	**$0**	**$464,000**	**$900,000**	**$1,364,000**	
	Share of costs relative to discounted credits	-	-	1.44%	1.65%	

countries, that is, upstream from emission reductions accounting. When evaluating compliance or/and when ERs are traded to offset emissions from other sources, uncertainty can also be discounted downstream to account for its impact on the value of those emission reductions, in order to ensure that real and credible reductions are met. By acting on uncertainty upstream or downstream of emission reduction accounting, the overall goal is to strengthen the environmental integrity of the system so that it can bring the full benefit it should provide in fulfilling the main of objective of the Convention on Climate Change.

4.1 Dealing with uncertainty upstream

Our results suggest that the global effort underway to improve forest monitoring systems in developing countries will contribute significantly to reduce uncertainties. Our simulations also showed that the cost of investing in MRV is compellingly low when compared to the potential income from selling carbon credits received from REDD+ under most discounting schemes. For Panama, it is clear that investing in improved forest monitoring capabilities is rational for scientific, environmental and financial reasons. It would allow the country to receive higher financial compensation from more certain emission reductions. The benefits of investing in forest monitoring systems will not only contribute to better scientific understanding of emissions and ER from deforestation and forest degradation and to better constrain uncertainty. It will contribute to provide a sound feedback to national policymakers to design effective environmental policy to slow and halt deforestation and forest degradation. Improved forest monitoring systems can serve to better attribute emissions from land-use change to specific drivers, actors or industries and contribute to national land-use planning processes.

4.2 Integrating uncertainty assessment in the current measurement practices

The IPCC provides guidance for estimating uncertainty in the national GHG inventories, via either error propagation (Tier 1) or Monte Carlo analysis (Tier 2) (Hiraishi et al. 2006). Yet, in order to improve the estimation of the overall uncertainty, the error associated with the different components included in carbon accounting from forests should be measured and accounted for.

One major issue that limits a better estimation of the overall uncertainty on emissions and emission reductions is the lack of information and transparency about the accuracy assessment of land-cover change maps and the failure to systematically apply good practices for evaluating the error around the land change area estimates. In effect, accuracy measures for single-date land-cover maps are not indicative of the overall accuracy of the post-classified change map that is needed for assessing activity data. When good practices for estimating uncertainty of the land change area estimates are used, the variability of these estimates has been shown to have a drastic effect on carbon flux model outputs (Olofsson et al. 2013). In our Panama case study, information about accuracy assessment was absent. Transparent and statistically valid accuracy assessment should include estimates of accuracy of change, estimates of land change area adjusted for the classification error, confidence intervals associated with the accuracy and with the estimated area of change (Olofsson et al. 2014). These good practices should be used largely as they would improve the estimation of error around estimated area of change and thus, in GHG emissions and emission changes.

Chave et al. (2004) provide also an excellent example of what is needed for estimating and partitioning the different sources of error in forest biomass estimation from ground inventory plots. This method should be replicated in other countries as error components may vary according to geographic regions and forest types. Important international work to compile existing allometric models in order to better circumscribe the level and distribution of uncertainty from the conversion of ground forest inventory measurements to biomass is also key (Henry et al. 2013). When different data sources are available, it is useful to compare the extent and location of the differences observed. For example, Ometto et al. (2014) compared different carbon maps available for the Brazilian Amazon and identified an inter-map differences of up to 50 %, showing the substantial impact that inter-map variability can have on emission estimates.

For forest degradation, the error estimated is still hard to circumscribe for both activity data and emission factors. The uncertainty estimated around ER from forest degradation should be interpreted as a first attempt to provide an error assessment from this source. Empirically-based information about error is lacking and should be prioritized to orient decision-making about monitoring choices in light of overall upstream uncertainty reduction improvements (Herold and Skutsch 2011; Ometto et al. 2014). This study takes place in a context where major emission reductions were produced from curbing deforestation and the costs of monitoring are relatively limited. Similar research is needed for countries with low deforestation and largely inaccessible forested areas that may face higher monitoring costs and more limited potential credits from REDD+.

4.3 Dealing with uncertainty downstream

Our results using five proposed schemes to discount ER for uncertainty downstream of accounting unveil the delicate balance between protecting environmental integrity through a discount mechanism that would compensate for credible ER and incentivizing mitigation actions to reduce deforestation. The degree of conservativeness is crucial to stimulate upstream investments in forest monitoring improvements.

We found that the more stringent the discount for uncertainty, the higher the incentive to invest in error reduction. For example, using a higher degree of conservativeness to discount for uncertainty makes it more attractive to reduce uncertainty, since it allows obtaining better payments. Our results show that only the Conservativeness Approach at 5 and 15 % percentile and the Risk Charge Approach at 95 and 85 % percentile consistently provide financial incentive to reduce error. When the discount is based on a lower degree of conservativeness, it can lead to fallacious cases where reducing error can generate lower credits than not reducing it. This is the case for the FCPF Carbon Fund Approach which discount less than all other scheme tested and do not motivate upstream investments. Since a change in accuracy affects the quantity of ERs calculated by increasing or decreasing it, in order to provide incentives for upstream forest monitoring improvements, the degree of conservativeness or downstream discount for uncertainty has to be sufficiently important so that reducing error leads to greater compensation. On the other hand, more stringent discounts also reduce the incentive for countries to undertake ER. And if discounts are too strict, countries could possibly forgo emission reduction programs entirely. We have not considered these effects in this analysis; we assumed that the emission reduction is invariant regardless of the downstream discounting approach employed.

While it is important to integrate incentives to take uncertainty into account when carbon is traded and for compliance, a balance should be struck such that action is not discouraged by increasing complexity and transaction costs unnecessarily. The Risk Charge Approach, which is equivalent to the Conservativeness approach and flexible about the confidence levels used, seems attractive because it is a generic approach that could apply to all sectors, not only to REDD+. Then, this proposal does not specify who should have to pay for the risk, the buyer or the seller of ERs, a question also raised by Knoke (2013) who uses the term insurance fees instead of risk charge. In the REDD+ context, it is often assumed that developing countries would receive less payment if ER are more uncertain, but under this scheme, the buyer of those ER could also be covering monetarily the risk associated with those ERs. Knoke (2013) underscores that an agreement should be reached about who should pay the insurance charge to obtain guaranteed emission reductions.

The comparison of those schemes allowed us to test between an adjustment determined in a step-wise manner based on uncertainty bands (or conservative factors) and an adjustment calculated on a continuous basis where the deduction is calculated based on the actual uncertainty value (as for the Conservativeness and Risk charge approach). The advantage of continuous approaches over the tabulated conservative factors is that they are more responsive to changes in uncertainty levels since every reduction of error is reflected in the amount of credits generated. Step-wise tabulated approaches could provide disincentives to adopt better measurement methods if uncertainty reduction leads to the same bracket of conservative discount.

Using these simulations, we quantified a first lower threshold above which it is economically and practically feasible to reduce uncertainty around ER from deforestation. This result brings up an important question about whether downstream discount should only be applied if the uncertainty exceeds a certain threshold (UNFCCC 2012). If the goal of applying discounting approach is to incentivize improved forest monitoring, discounting below a certain threshold would be punitive for REDD+ countries. Discounting for uncertainty below the uncertainty threshold quantified is not likely to serve as an incentive for further improvements in forest monitoring, especially if the error is a reflection of the characteristic variability of what is being measured or if it represents the limit of the instrumentation used. However, if the goal of using adjustment for uncertainty is to allow comparing ERs between different sectors of activities by ascribing a value to uncertainty, deductions could be applied over the whole uncertainty range.

5 Conclusion

By acting on uncertainty upstream or downstream of emission reduction accounting, the aim is securing the environmental integrity in compliance and trading. This study shows that:

1) The cost of reducing uncertainty upstream of carbon accounting through investment in MRV is small in comparison to the potential credits that could be generated for reducing emissions from deforestation and forest degradation.
2) The assessment of the error around all the different inputs needed for accounting should become an integral part of measurement practices in order to circumscribe the uncertainty better and have the ability to constrain it.
3) For downstream uncertainty discounting approach, the degree of conservativeness is central to stimulate both improvements upstream and mitigation actions. It needs to neither too stringent, by generating no positive incentive, nor too loose, by creating no incentive to reduce uncertainties.
4) The Conservativeness Approach and the Risk Charge approach (at some specific confidence levels) are the only discounting schemes that provide consistent financial incentives for reducing uncertainty upstream.

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References

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

Bartoszczuk P, Horabik J (2007) Tradable permit systems: considering uncertainty in emission estimates water, air, & soil pollution. Focus 7:573–579

Canadell JG et al (2010) Interactions of the carbon cycle, human activity, and the climate system: a research portfolio. Curr Opin Environ Sustain 2:301–311

CATHALAC (2009) Informe final de actualización de la cobertura boscosa de la República de Panamá 2008. República de Panamá, Panamá

Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R (2004) Error propagation and scaling for tropical forest biomass estimates. Phil Trans Royal Soc London Ser B-Biolo Sci 359:409–420

FCPF (2013) FCPF carbon fund methodological framework. The World Bank, Washington, DC

GFOI (2013) Integrating remote-sensing and ground-based observations for estimation of emissions and removals of greenhouse gases in forests. Methods and Guidance from the Global Forest Observations Initiative. Group on Earth Observations, Geneva, 2014

Gillenwater M, Sussman F, Cohen J (2007) Practical policy applications of uncertainty analysis for national greenhouse gas inventories water. Air Soil Pollut Focus 7:451–474

GOFC-GOLD (2012) A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation. GOFC-GOLD Land Cover Project Office, Wageningen University, The Netherlands

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. Environ Res Lett 3:035005 (035012 pp.)

Grassi G, Federici S, Achard F (2013) Implementing conservativeness in REDD+ is realistic and useful to address the most uncertain estimates. Clim Change 119:269–275. doi:10.1007/s10584-013-0780-x

Gutierrez R (2010) Forest resource assessment 2010: country report Panama vol National Report FRA2010/160. FAO, Rome

Henry M (2013) GlobAllomeTree: international platform for tree allometric equations to support volume, biomass and carbon assessment. iForest 6:326–330

Herold M, Skutsch M (2011) Monitoring, reporting and verification for national REDD plus programmes: two proposals. Environ Res Lett 6 doi:10.1088/1748-9326/6/1/014002

Hewson J, Steininger M, Pesmajoglou S, eds. (2013) REDD+ Measurement, reporting and verification (MRV) Manual. USAID-supported forest carbon, markets and communities program, Washington, DC, USA

Hiraishi T et al. (2006) Quantifying uncertainties in practice. In: IPCC (ed) IPCC Good practice guidance and uncertainty management in national greenhouse gas inventories

IPCC (2003) Good practice guidance for land use, land-use change and forestry. Institute for Global Environmental Strategies (IGES), Hayama

IPCC (2006) IPCC guidelines for national greenhouse gas inventories vol 4. Institute For Global Environmental Strategies, Japan

Jonas M, Marland G, Winiwarter W, White T, Nahorski Z, Bun R, Nilsson S (2010a) Benefits of dealing with uncertainty in greenhouse gas inventories. Introd Clim Change 103:3–18

Jonas M, White T, Marland G, Lieberman D, Nahorski Z, Nilsson S (2010b) Dealing with uncertainty in GHG inventories: how to go about it? In: Marti K, Ermoliev Y, Makowski M (eds) Coping with uncertainty: robust solutions. Springer, Heidelberg, pp 229–245

Jonas M, Marland G, Winiwarter W, White T, Nahorski Z, Bun R, Nilsson S (2011) Lessons to be learned from uncertainty treatment: conclusions regarding greenhouse gas inventories. In: White T, Jonas M, Nahorski Z, Nilsson S (eds) Greenhouse gas inventories: dealing with uncertainty. Springer, Dordrecht, Netherlands, pp 339–343

Knoke T (2013) Uncertainities and REDD+: implications of applying the conservativeness principle to carbon stock estimates. Clim Change 119:261–267

Le Quéré C, Raupach MR, Canadell JG, Marland G (2009) Trends in the sources and sinks of carbon dioxide. Nat Geosci 2:831–836

Lieberman D, Jonas M, Winiwarter W, Nahorski Z, Nilsson S (2007) Accounting for climate change. Introd Water Air Soil Pollut 7:421–424

Marland G, Hamal K, Jonas M (2009) How uncertain are estimates of CO2 emissions? J Ind Ecol 13:4–7

Marland E, Cantrell J, Kiser K, Marland G, Shirley K (2014) Valuing uncertainty part I: the impact of uncertainty in GHG accounting. Carbon Manag 5:35–42

CDM Methodologies Panel (2008) Draft guidance on how to deal with uncertainties in emission reduction calculations (MP32, Annex 14)

Nahorski Z, Horabik J, Jonas M (2007) Compliance and emissions trading under the kyoto protocol: rules for uncertain inventories water. Air Soil Pollut Focus 7:539–558

Olofsson P, Foody GM, Stehman SV, Woodcock CE (2013) Making better use of accuracy data in land change studies: estimating accuracy and area and quantifying uncertainty using stratified estimation. Remote Sens Environ 129:122–131

Olofsson P, Foody GM, Herold M, Stehman SV, Woodcock CE, Wulder MA (2014) Good practices for estimating area and assessing accuracy of land change. Remote Sens Environ 148:42–57

Ometto JP et al (2014) Amazon forest biomass density maps: tackling the uncertainty in carbon emission estimates. Clim Change 124:545–560

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

Pelletier J, Martin D, Potvin C (2013) REDD+ CO2 flux estimation and reporting for early actions: dealing with uncertainty. Environ Res Lett 8:034009

Plugge D, Baldauf T, Köhl M (2013) The global climate change mitigation strategy REDD: monitoring costs and uncertainties jeopardize economic benefit. Clim Change 119:247–259

Romijn E, Herold M, Kooistra L, Murdiyarso D, Verchot L (2012) Assessing capacities of non-annex I countries for national forest monitoring in the context of REDD+. Environ Sci Policy 19-20:33–48

UNFCCC (2003) Technical guidance on methodologies for adjustments under Article 5, Paragraph 2, of the Kyoto Protocol (FCCC/SBSTA/2003/10/Add.2). United Nations Framework Convention on Climate Change

UNFCCC (2005) Good practice guidance and adjustments under Article 5, paragraph 2, of the Kyoto Protocol Decision 20/CMP1 FCCC/KP/CMP/2005/8/Add.3

UNFCCC (2010) The Cancun agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. United Framework Convention on Climate Change

UNFCCC (2012) Concept note: Uncertainty of measurement in baseline and monitoring methodologies vol CDM, EB 68, Annex 10

VCS (2013) VCS standard, VCS version 3, requirements document, 8 October 2013, v3.4. Verified Carbon Standard