Robust design of multi-scale programs to reduce deforestation[*]

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Annex 1: A visual representation of the error structure across scales

Figure A1.1 provides a schematic representation of the components of the error in aggregating from sub-national activities to a national level. The distinction is made between errors in reference levels and errors in implementation. Since we are focusing here on errors in reference levels, only that side of the "error-tree" is developed. For notational simplicity everything below the regional level is represented as the sum of the reference level errors for implementing entities in each region; however, one could branch out further and show the different scale of implementing entities below the regional level, but this would complicate the figure without adding much conceptually. The important difference relative to Figures 1-3 in the main text of the paper, which were just portraying the causal link between reference levels, is that here at each scale there will be an additional term "closing" the credit accounting at each scale. For example, at the national scale there will be the regional reference level errors ($e\_ref_{REG\_i}$), but there is also a reference level error that is associated with the national government (e_ref_{NGOV}). The sum of all these errors will equal the national reference level error (e_ref_{NAT}).

[*] The author would like to thank two anonymous reviewers, Jonah Busch, Ruben Lubowski, Daniel Nepstad, Tracy Johns, and participants in seminars held at the World Bank, and at the Amazon Environmental Research Institute (IPAM).

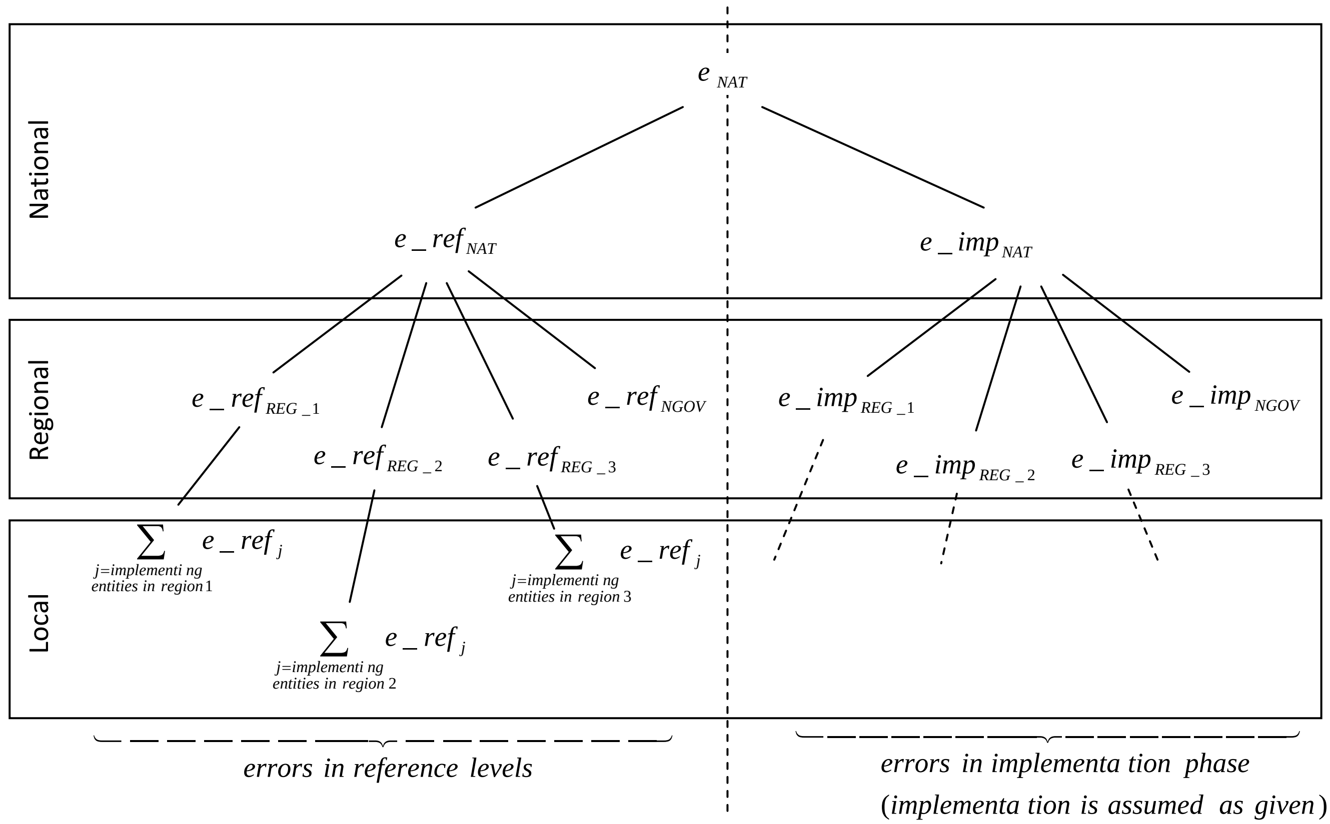

Figure A1.1. *Components of the error in aggregating from sub-national activities to a national level: errors in reference levels and in implementation*

Annex 2: Proof of Propositions 1 and 2

Proof – The truth of the first proposition is intuitively obvious. But since the theorem makes a claim about all possible instances of REDD institutional arrangements under certain conditions, and since the REDD architecture's institutional arrangements are recursively defined through an aggregation process that goes from individual stakeholders all the way to the national government, *formally* it must be proved by structural induction . The second proposition follows from the first because a cap-and-trade mechanism imposes participation, and is by definition internally consistent.

The proof of the first proposition is by structural induction, which is required when proving a claim about a recursively-defined set. The tree describing the REDD architecture can be constructed as a recursively-defined set over a set of base cases. The base cases in our problem will be the individual stakeholders, constituting the most disaggregated scale, and the implementing entities at the scale immediately above individuals. The self-referential cases constructed by aggregating base cases into the full REDD reference level architecture are called induction cases.

We assume that the incentive level is fixed and that implementation strategies are decided and carried out. The reference level only affects the amount of emissions reductions credited to each implementing entity. In reality reference levels affect also participation, but here we assume that participation is given. Reference levels do not affect the marginal incentive to reduce emissions. If participation is given (as in proposition 1) then proving scale neutrality is equivalent to proving that the credits received specifically by scale *i*, are not affected by the reference levels adopted at more disaggregated scales.

The claim must hold for any REDD institutional tree structure (T). So assume that an arbitrary institutional arrangement, *T*, is provided. If *T* has the shape of a base case (i.e., no substructures that are *T*s) then we show how we can deduce the claim immediately. Otherwise, we must rely on induction and assume the claim for substructures within *T*, and then deduce the claim. The claim then holds for all *T* by the principle of structural induction. The proof is therefore in two steps: first we prove the "base case", that if crediting reference levels at the individual stakeholder scale (i=1) are consistent with those at scale i+1 then scale neutrality holds at the most disaggregated scale in the REDD architecture. Then we must prove that scale neutrality holds for the result of any recursive combination rule assuming that scale neutrality holds for all constituent parts (base cases).

Let R_i be the residual credits or debits at scale i after having subtracted credits allocated to scales below i. Using the total derivative we can write:

$$\frac{\partial R_i}{\partial e_{j,s}} = \frac{\partial R_i}{\partial e_{j,s}} + \sum_{t \neq s} \frac{\partial R_i}{\partial e_{j,t}} \cdot \frac{\partial e_{j,t}}{\partial e_{j,s}}$$

An additional unit in the error of the reference level of stakeholder *s* will reflect proportionately (with a negative effect) on the residual credits available at the scale above the stakeholder; therefore the first term on the right hand side will equal -1. The same applies to the error in reference levels for all other stakeholders *t*. So the equation above can be written as:

$$\frac{\partial R_i}{\partial e_{j,s}} = -1 + (-1)\sum_{t \neq s} \frac{\partial e_{j,t}}{\partial e_{j,s}}$$

However, if there is to be internal consistency from the individual stakeholders then $\sum_{t \neq s} \frac{\partial e_{j,t}}{\partial e_{j,s}} = -1$ because any change in reference level for one stakeholder will have to be counterbalanced by adjustments to the reference levels of other stakeholders, otherwise the assumption of internal consistency across scales no longer holds.[1] To conclude this implies that $\frac{\partial R_i}{\partial e_{j,s}} = 0$, and therefore scale neutrality holds for the base cases.

Induction cases: Suppose that the claim of scale neutrality is true for trees X and Y, then we must show that scale neutrality is true for the tree formed by joining the two trees into one. Let *p*,*q*, and *r* be the root , and they are jointly internally consistent with the reference level at scale *i* and the allocation of credits specifically to scale *i*, then the same reasoning applies as for the base cases presented in the previous part of the proof.

[1] We are implicitly assuming strict internal consistency here (ie. that the summing up condition across scales is binding in reference levels). This is acceptable even though the proposition only assumes internal consistency, because as mentioned in the main text of the paper, and as expressed in Figure 4, we assumed a “closing” stakeholder at each scale that effectively makes it binding.

Annex 3: Shedding light on the different design options: The BANTER model

The *Brazilian Amazon Negotiation Toolbox for the Economics of REDD* (BANTER) is a partial equilibrium model intended to inform users about the environmental and financial impact of different policy design options at the level of the Brazilian Amazon states. The first step towards making REDD and Amazon-wide program is for states to agree on a system of reference levels that is environmentally effective, economically efficient, and perceived as fair.

The analytical framework for BANTER follows that of the Open Source Impacts of REDD Incentives platform (OSIRIS). It is a stylized one-period partial equilibrium market for a single composite commodity, adapted from Murray (2008). Following Busch *et al.* (2009), the commodity in the BANTER model is the output of agriculture, including a one-time timber harvest, produced on one hectare of land cleared from the tropical forest frontier. Expansion of the agricultural frontier is assumed to be responsible for deforestation, which is a plausible assumption in the Brazilian case. .

Demand for frontier agriculture is at the national level, with underlying national demand for agriculture and timber perfectly substitutable between domestic and imported agricultural production. For each of the 9 Brazilian Amazon states, we construct a statewide supply curve for frontier agriculture in the absence of REDD incentives based on spatially explicit rent models of economic returns to soy, livestock, and timber (Soares-Filho *et al.*, 2006). State-level supply curves sum horizontally to determine a national supply curve for frontier agriculture. National supply and demand curves intersect to determine the economic return to frontier agriculture in Brazil and the quantity of annual deforestation. We assume that each state chooses the quantity of frontier agriculture that maximizes its national surplus from agriculture and REDD carbon payments.

The impact of REDD incentives on deforestation is modeled by shifting state-level supply curves for frontier agriculture inward and upward, as the relative return to frontier agriculture is diminished by the opportunity cost of obtaining REDD credits from standing forest. The reduced national supply curve intersects with the global demand curve to predict the national increase in the return to frontier agriculture, and the change in the quantity of frontier agriculture supplied by each state. In Amazon states where REDD provides sufficient incentives to retain standing forest, the estimated quantity of frontier agriculture supplied decreases. Conversely, in states where weak or non-existent REDD incentives are outweighed by increased returns to agriculture, the estimated quantity of deforestation increases as agricultural production expands. A state's quantity of deforestation, reference level and estimated average forest carbon density are used to calculate the country's reductions in emissions from deforestation and REDD revenue.

Real uncertainties exist about the future market price of carbon, transaction and management costs, and especially the elasticity of demand for frontier agriculture. In the case of BANTER the elasticity of demand was obtained by simulating changes in the price of newly deforested land using a regional computable general equilibrium model (Cattaneo, 2001) These and other uncertainties are treated transparently in BANTER through the use of flexible parameters which can be changed by users. The analysis presented here is preliminary and should be followed by a sensitivity analysis for key parameters.

Annex 4: Deviation from historical emissions and from the business-as-usual of different reference level approaches

In the context of the empirical example using BANTER, it is useful to analyze how the reference levels deviate from the historical emissions during the crediting period. For the perfect-foresight case the adjustment relative to historical represents the fact that the BAU can deviate substantially from historical emissions, and it illustrates the case in which the reference level correctly predicts the BAU, and therefore this scenario has no reference level error (Table A4.1). However, this is only an ideal benchmark. In the historical emissions reference level without any adjustments the discrepancy between the expected BAU and the actual BAU is captured by the error in reference level (Table A4.1).

Table A4.1. *Uncertainty in business-as-usual and errors in reference levels*
Five approaches for setting reference levels are compared in terms of (i) the adjustment in crediting reference levels for the crediting period (2000-2005) relative to business-as-usual in the reference period (1990-2000), (ii) the error in crediting reference level for the crediting period (2000-2005)

		Acre	Amazonas	Mato Grosso	Pará	Rondônia	Total for all 9 Brazilian Amaz. States
Perfect Foresight	Ref. level adjustment relative to historical (% of BAU)	30%	22%	41%	28%	35%	31%
	Error in reference level (as % of BAU)	0%	0%	0%	0%	0%	0%
Historical - no adjustment	Ref. level adjustment relative to historical (% of BAU)	0%	0%	0%	0%	0%	0%
	Error in reference level (as % of BAU)	-30%	-22%	-41%	-28%	-35%	-31%
Combined Incentives	Ref. level adjustment relative to historical (% of BAU)	2%	85%	-6%	-2%	-7%	2%
	Error in reference level (as % of BAU)	-29%	63%	-47%	-30%	-41%	-29%
Stock flow (15% withholding)	Ref. level adjustment relative to historical (% of BAU)	8%	65%	2%	6%	2%	8%
	Error in reference level (as % of BAU)	-22%	43%	-39%	-22%	-33%	-23%
Cap-and-trade: historical allocation	Ref. level adjustment relative to historical (% of BAU)	0%	0%	0%	0%	0%	0%
	Error in reference level (as % of BAU)	-30%	-22%	-41%	-28%	-35%	-31%

Reference level designs such as combined incentives, and the flow withholding and stock payment approach, were initially designed to address issues of leakage at the international level. When transposed to a sub-national level to determine reference level for states in the Brazilian Amazon, these reference levels tend to overcompensate the adjustment for low-deforestation rate states, such as Amazonas where we see an adjustment of the “Expected BAU” relative to historical that overshoots the actual BAU. This implies that the sign on the error in the reference level for becomes positive as there is some slack in the reference level relative to the actual BAU. The flow-withholding and stock payment approach allows for some additional overall reference level emissions, by paying for emissions reductions at a slightly lower rate. In the specific case we are analyzing, where emissions are increasing over time, this particular trait of the flow-withholding and stock payment approach means that the reference level errors for all states are lower in magnitude than for either the historical emission or the combined incentives reference levels.