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Environmental and socio-economic consequences of forest carbon payments in Bolivia: Results of the OSIRIS-Bolivia model[⊗]

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Abstract:

Bolivia has significant potential to abate climate change by reducing deforestation. This opportunity presents economic and environmental tradeoffs. While these tradeoffs have been hotly debated, they have as yet been the subject of little quantitative analysis. We introduce the OSIRIS-Bolivia model to provide a quantitative basis for decision-making. OSIRIS-Bolivia is an Excel-based tool for analyzing the potential effects of incentive payments to reduce emissions from deforestation (REDD) in Bolivia. It is based on a spatial econometric model of deforestation in Bolivia during the period 2001-2005, and uses information on forest cover, deforestation rates, geographical conditions, and drivers of deforestation, including agricultural opportunity costs, for more than 120,000 pixels covering the whole country. OSIRIS-Bolivia is based on a partial equilibrium model in which reductions in deforestation in one region reduce the supply of agricultural products to the domestic market, which in turn causes an increase in the price of agricultural products, making conversion of land to agriculture more attractive and thus stimulating an increase in deforestation in other regions (leakage). The model can help answer questions such as: Where in Bolivia are carbon incentive payments most likely to result in reduced deforestation? Who are most likely to benefit from REDD? How much money will it take to reduce deforestation by a given amount? To what extent might transaction costs or preferences for agricultural income undermine the goals of the REDD program?

Keywords: Deforestation, REDD, environmental impacts, socio-economic impacts.
JEL classification codes: Q21, Q56.

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1. Introduction

With 57 million hectares of forest[1], Bolivia ranks 7th in the world in terms of extent of tropical rainforest and is among the dozen countries with highest terrestrial biodiversity[2]. However, deforestation rates have increased rapidly during the last three decades and more than 300,000 hectares of forest are lost annually[3], mostly due to the expansion of the agricultural frontier[4]. In addition, logging[5] and uncontrolled fires are degrading large parts of the remaining forest. More than 80% of the deforestation and logging taking place is illegal[6], thus contributing little tax revenue to the government[7] and causing much harm to the local and global environment[8], as well as to the indigenous forest peoples[9].

Given the volume of greenhouse gas emissions resulting from these deforestation rates[10], Bolivia has been selected by both UN-REDD and the Forest Carbon Partnership Facility (FCPF) to receive funds to prepare for an international mechanism of incentives to reduce emissions from deforestation and forest degradation (REDD). Likewise, the country has received substantial funds (or promises of funds) from bilateral sources in support of the preparation process (most notably from the governments of Germany, Denmark and the Netherlands).

Bolivia is in many ways a pioneer in initiatives to reduce deforestation. The first debt-for-nature swap in the world took place in Bolivia in 1987, and Bolivia hosted the Noel Kempff Climate Action Project, which in 2005 became the first voluntary carbon project to achieve verified emissions reductions from reduced deforestation. In addition, about 15 million hectares of forest have been declared national parks or some other type of protected area and about 20 million hectares have been communally titled to various indigenous forest peoples[11]. The country has participated actively in the United Nations Framework Convention on Climate Change (UNFCCC) negotiations on REDD since they began in 2005, and it was one of the first countries to have its Readiness Plan Idea Note (R-PIN) approved by FCPF (Paris, July 2008). Its UN-REDD document was approved in Nairobi in March 2010.

If Bolivia could successfully reduce emissions from deforestation by just one quarter compared to actual levels, the compensation it could receive from participating in an international REDD mechanism would be substantial. For example, assuming a conservative carbon value of \$10/tCO_2, the annual compensation for a 25% reduction in emissions would amount to more than \$400 million, surpassing the GDP of the entire industrial agriculture sector.[12]

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[1] FAO (2010).
[2] Ibisch & Mérida (2003).
[3] Killeen et al. (2007) and FAO (2010).
[4] Killeen et al. (2008).
[5] Pacheco (2010).
[6] Information from the Bolivian Autoridad de Fiscalización y Control Social de Bosques y Tierras (ABT).
[7] Jemio (2011).
[8] Deforestation causes global damages mainly through CO_2 emissions, and local damages mainly through the loss of habitat for biodiversity and the increase in wildfires (Andersen 2002; Andersen 2009)
[9] The threat to indigenous forest peoples is mainly due to encroachment by settlers, who use deforestation to claim land titles (Roper 2003)
[10] According to Ruesch & Gibbs (2008), the average carbon contents for Bolivian forests is 150 tC/ha, which is equivalent to 550 tCO_2/ha. The average subsequent land use contains about 10 tCO_2/ha, so annual emissions from deforestation amounts to about (550-10)*300,000 = 162 million tCO_2/year.
[11] Bolivia (2009). There is a 2 million hectare overlap between Indigenous Territories and Protected Areas.
[12] According to the National Statistical Institute (www.ine.gob.bo), the GDP of Industrial Agriculture in 2010 amounted to \$357 million.

However, the REDD mechanism was forcefully rejected by participants at the World People's Conference on Climate Change and the Rights of Mother Earth in Cochabamba in April 2010. The resulting People's Agreement states:

> "We condemn market mechanisms such as REDD (Reducing Emissions from Deforestation and Forest Degradation) and its versions + and + +, which are violating the sovereignty of peoples and their right to prior free and informed consent as well as the sovereignty of national States, the customs of Peoples, and the Rights of Nature."

The Government of Bolivia is taking this outcome very seriously, and the REDD preparation process in Bolivia has grinded almost to a halt. For example, a recent official submission from the Plurinational State of Bolivia to the UNFCCC states in point 8(e): "in all actions related to forest, the integrity and multifunctionality of the ecological systems shall be preserved and no offsetting or market mechanisms shall be applied or developed."[13]

It is clear that much internal consultation and analysis is necessary in order to fully understand the potential positive and negative effects of REDD in Bolivia. Only by thoroughly understanding the potential benefits and costs of REDD is it possible to make an informed decision and carefully tailor the mechanisms and incentives in a participatory manner so as to maximize the positive effects and minimize the negative side effects.

The OSIRIS-Bolivia tool[14] has been developed to contribute to this analysis and discussion of positive and negative effects of a REDD mechanism in Bolivia. The tool interprets REDD in its original performance-based conception of paying for the reduction of emissions from deforestation below an established reference level. Forest degradation and reforestation are not included in the tool, and neither are other types of incentives for reducing deforestation, like conservation contracts[15] or fines for illegal deforestation. It is assumed that finance for payments comes from international sources, which could be either a bilateral fund or a carbon market.

The present paper explains how the OSIRIS-Bolivia tool works and shows what kind of questions the tool can help answer. These questions include the costs of reducing deforestation, the distributional impacts of REDD, the identification of winners and losers, and trade-offs between reducing emissions and reducing poverty. It is worth noting here that these issues are not unique to Bolivia, but extend to other forest countries that are designing policies and evaluating the trade-offs of REDD.

The remainder of the paper is organized as follows: Section 2 explains the key equations underlying OSIRIS-Bolivia and Section 3 presents the spatial econometric model of the drivers of deforestation, which constitutes the basis of the model. Section 4 shows what kind of questions OSIRIS-Bolivia can help answer. Finally, Section 5 provides conclusions, policy recommendations, and directions for further research.

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[13] FCCC/AWGLCA/2011/CRP.23, dated 4 October 2011.

[14] Andersen et al. (2012).

[15] Conservation incentives in the form of payments to land owners who sign long term conservation contracts are analyzed in a companion tool called CISS-Bolivia (Conservation Incentives Spread Sheet for Bolivia), which can also be downloaded from the website: www.conservation.org/OSIRIS.

2. Modeling REDD incentives in OSIRIS-Bolivia

OSIRIS-Bolivia is adapted from OSIRIS-Indonesia (Busch et al. 2012) which in turn was developed from an 85-country international OSIRIS model (Busch et al. 2009). The national OSIRIS models are currently the most sophisticated economic tools available for the evaluation of the potential effects of REDD policy decisions. They include several important methodological advances on previous models that have estimated the emission reduction potential of REDD. First, most previous studies have relied upon a deterministic "opportunity cost" assumption that deforestation would be avoided entirely wherever potential carbon payments exceed net revenue from alternative land uses (Platinga et al. 1999; Grieg-Gran 2006; Kindermann et al. 2008; Busch et al. 2009; Butler et al. 2009; Venter et al. 2009; Soares-Filho 2010; World Bank Institute 2011). In contrast, OSIRIS calibrates the marginal impact of potential carbon payments on deforestation using the empirical relationship between the pattern of observed deforestation in a historical period and spatial variation in the benefits and costs of converting land from forest to agriculture. Using this "revealed preference" approach to estimate the impact of potential payments based on evidence from actual land-use decisions, implicitly accounts for the richer set of factors that affect land-use in practice (Stavins 1999; Lubowski et al. 2006; Pfaff et al. 2007; Warr & Yusuf 2011). Second, most previous studies have modeled land-use responses to variations in a single parameter—the carbon price. By modeling land-use response to variations in both the carbon price and sub-national reference levels, and modeling participation decisions at multiple geographic scales, we are able to compare a wider range of potential policies for implementing REDD within a country. Third, as in global partial equilibrium (Borner & Wunder 2008; Butler et al. 2009) or general equilibrium (Soares-Filho et al. 2010; Murray 2008) models, but unlike other opportunity cost (Kindermann et al. 2008) or regional (Golub et al. 2009) analyses, we model the "leakage" of deforestation (Angelsen & Wertz-Kanounnikoff 2008) within the country, whereby reduced deforestation in one region produces market feedbacks that increase deforestation elsewhere. Finally, unlike previous qualitative discussions of multi-scale REDD incentive policies (Pedroni et al. 2009; Cortez et al. 2010; FAO 2010), we are able to quantify and map the impacts of policy decisions within a particular country (Busch et al. 2012).

OSIRIS-Bolivia is built around a country-specific deforestation model (eq. 1), which predicts the probability of deforestation at each site, i, in the absence of REDD incentives, based on observable site characteristics:

$$y_i = \exp(\beta_0 + X_i'\beta_1 + \beta_2 \ln(A_i) + \epsilon) \quad (1)$$

Here $y_i = (F_i^o - F_i^{'})/F_i^o$ is percent deforestation at site *i*, where F_i^o is forest cover at site *i* at the start of the 2001-2005 observation period, and $F_i^{'}$ is forest cover at site *i* at the end of the observation period. X_i is a matrix of observable geographic site characteristics related to initial forest cover, access, topography, and other geographic factors explained in detail in the following section. A_i is the net present value of potential net agricultural revenue per hectare at site *i* (adapted from Naidoo & Iwamura 2007). Unlike OSIRIS-Indonesia, we use net instead of gross agricultural revenue (net revenues are assumed to be 33% of gross revenues, as suggested by Leguia, Malky & Ledezma (2011)) and we take the natural logarithm due to the decreasing marginal utility of income. The net present value is calculated with a 10% discount rate under the assumption of 5 consecutive years of cultivation and then 15 years of fallow with no agricultural revenues. This corresponds to the average length of cultivation observed across all crops in the department of Santa Cruz, Bolivia according to Andersen (2006). Finally, the constant term β_0 captures unobserved components of the expected net benefits of deforesting site j.

The predicted probability of deforestation at site *i* in the absence of REDD, $\hat{y}_{i,NOREDD}$, is then given by:

$$\hat{y}_{i,NOREDD} = \exp(\hat{\beta}_0 + X_i'\hat{\beta}_1 + \hat{\beta}_2 \ln(A_i)) \quad (2)$$

The spatial distribution across the country of $\hat{y}_{i,NOREDD}$ for all cells constitutes the Business-as-Usual (BAU) reference scenario in OSIRIS-Bolivia, whereas the distribution of y_i constitutes the historical reference scenario. If $\hat{\beta}_2 > 0$, which is the case in Bolivia, then higher potential net agricultural revenues imply higher probability of deforestation, as theory and empirics suggests (Barbier, 2001).

The REDD mechanism is designed to raise the relative attractiveness of standing forest compared to agriculture by providing payments for keeping land as forest. Assuming that one dollar received from REDD payments has an equal and opposite impact on the probability of deforestation as one dollar received from agricultural profits, we can deduct marginal REDD revenue per hectare, RR_i, from A_i when simulating the effect of REDD. Thus, if a site chooses to opt into the REDD mechanism, the opportunity costs of maintaining forest would be lower and the probability of deforestation would therefore also be lower. However, there is another effect that works in the opposite direction, which is that an increase in agricultural prices, τ_1, due to the reduction in deforestation and reduction in agricultural supply at the forest frontier caused by REDD, would make agriculture relatively more attractive.

Thus, if a site opts into REDD, the probability of deforestation is given by equation (3):

$$\hat{y}_{i,REDD,opt\ in} = \exp(\hat{\beta}_0 + X_i'\hat{\beta}_1 + \hat{\beta}_2 ln((1+\tau_1)A_i - RR_i)) \quad (3)$$

The REDD revenue per hectare accruing to a site which has opted into REDD is given by:

$$RR_i = p_{CER} * (1-r) * ER_i \quad (4)$$

where p_{CER} is the price paid by international buyers for carbon emission reductions, $r \in [0,1]$ is the portion of world carbon price withheld by the national government under a revenue sharing arrangement (e.g. r = 0 would signify that carbon payments accrue entirely to the site), and ER_i is the emissions reductions achieved at site *i* (tCO_2e/ha).

The increase in national agricultural prices, τ_1, is modeled endogenously in OSIRIS-Bolivia and depends on an "effective elasticity" parameter, which is functionally equivalent to the price elasticity of exponential demand for frontier agriculture (Busch et al. 2009), but is assumed to also incorporate feedback in the domestic labor and productive capital markets:

$$\tau_1 = \left(\frac{D_{NOREDD}}{D_{REDD}}\right)^e \quad (5)$$

where D_{NOREDD} is the total amount of deforestation in the country without REDD (i.e. the national reference level) and D_{REDD} is the total amount of deforestation in the country with REDD.

The default value chosen for the effective elasticity parameter in OSIRIS-Bolivia is 1.4, which yields a leakage of approximately 6%. This is in the low end of the admittedly wide leakage range estimated (2% - 40%) for the REDD-like project carried out to expand the Noel Kempff Mercado national park in Bolivia (Sohngen & Brown 2004).

Some sites/municipalities may choose to opt out of REDD because the agricultural net revenues they can gain are higher than the gains from participating in REDD. For these sites/municipalities, the probability of deforestation is given by:

$$\hat{y}_{i,REDD,opt\ out} = \exp(\hat{\beta}_0 + X_i'\hat{\beta}_1 + \hat{\beta}_2 ln((1 + \tau_1)A_i)) \quad (6)$$

The site/municipality's gains from participating in the REDD mechanism depend not only on the opportunity costs, but also on the reference emissions level, REL_i, which would be the reference deforestation level multiplied by the site specific emissions factor, E_i.

The site specific emissions factors are calculated from maps of carbon contents in the natural vegetation, $C_{veg,i}$, in the soil, $C_{soil,i}$, and in the typical subsequent land use, C_{ag}:

$$E_i = 3.67 * [(C_{veg,i} - C_{ag}) + \varphi C_{soil,i}] \quad (7)$$

where φ is the share of soil carbon that is assumed to be emitted due to the land use change.

The site level participation decision is determined by a comparison of net revenues from opting in and opting out of REDD. The site decides to opt in if:

$$p_{CER} * (1 - r)[RL_i - \hat{y}_{i,REDD,opt\ in} * F_i^o * E_i] > \quad (8)$$

$$\gamma((\hat{y}_{i,REDD,opt\ out} - \hat{y}_{i,REDD,opt\ in}) * F_i^o * (1 + \tau_1) * A_i)$$

The parameter γ represents the population's preference for agricultural revenue relative to REDD revenue. If $\gamma = 1$, then a dollar of agricultural revenue is equivalent to a dollar of REDD revenue. Later we explore values of this parameter above or below 1.

3. A spatial econometric model of the drivers of deforestation

Table 1 describes in detail all the potential variables that correlate with deforestation considered for OSIRIS-Bolivia. This set of driver variables were evaluated at the pixel level, with the national territory of Bolivia gridded into 120,475 square pixels of 3×3 km.

Following Busch et al. (2012), we estimated the deforestation model in Stata 9 using a Poisson quasi-maximum likelihood estimator (Wooldridge 2002). A Poisson model tolerates zero values unlike a log-normal distribution, and generates a distribution of predicted values which fits the observed data distribution better than logit or OLS. This distribution is concentrated nearest to zero deforestation and diminishes toward greater levels of deforestation.

Table 1: Potential drivers of deforestation in Bolivia, 2001-2005

Dependent variable	**Unit**	**Source**	**Average value**	**Min – Max**
Forest loss between 2001 and 2005	Share of pixel	Fundación Amigos del Museo Noel Kempff Mercado, 2009 deforestation map.	0.028	0 – 1
Explanatory variables	**Unit**	**Source**	**Average value**	**Min – Max**
Initial forest cover in 2001	Share of pixel	Fundacion Amigos del Museo Noel Kempff Mercado, 2009 deforestation map.	0.556	0 – 1
Distance to roads	km	Grid map of distances calculated from the existing fundamental roads network from the ABC, 2010 RVF Map.	23.331	0 – 146
Distance to river	km	Grid map of distances calculated from the major, primary and secondary rivers according to SITAP, 2009.	12.444	0 – 149
Distance to urban center with more than 5.000 inhabitants	km	Grid map of distances calculated from the main populations according to INE, 2001.	90.100	0 – 327
Average slope of pixel	%	Average slope calculation from the SRTM V2 (2005) Digital elevation model.	10.022	0 – 89
Average altitude	m.a.s.l.	Average altitude calculation from the SRTM V2 (2005) Digital elevation model.	1229.852	0 – 5837
Average carbon contents in vegetation	tC/ha	Ruesch & Gibbs (2008).	89.081	0 – 193
Average carbon contents in soil	tC/ha	FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. *Harmonized World Soil Database (version 1.2)*. FAO, Rome, Italy and IIASA, Laxenburg, Austria.	9.325	0 – 144
Net Primary Productivity	kg C/m2/year	Average Net primary Production of 2001-2005 of grid maps from NTSG (Numerical Terradynamic Simulation Group).	11.738	0 – 60
Fire density	Thermal anomalies/ha	Density map of 2001-2006 MODIS observed thermal anomalies with more than 60% occurrence probability.	0.503	0 – 18
Population density	Inhabitants/ha	Density grid from 2001 census localities.	7.511	0 – 4118
Distance to already deforested pixel in 2001	km	Distance Grid from deforested pixels until 2001, from the Fundacion Amigos del Museo Noel Kempff Mercado, 2009 deforestation map.	37.032	0 – 397
Individual land title	Share of pixel	INRA (Instituto Nacional de	0.076	0 – 1

		Reforma Agraria), 2009		
Communal land title	Share of pixel	INRA (Instituto Nacional de Reforma Agraria), 2009	0.172	0 – 1
Public land	Share of pixel	INRA (Instituto Nacional de Reforma Agraria), 2009	0.170	0 – 1
Unclear land title	Share of pixel	INRA (Instituto Nacional de Reforma Agraria), 2009	0.568	0 – 1
Protected area	Dummy if present within pixel	SERNAP (Servicio Nacional de Areas Protegidas).	0.173	0 – 1
Human Development Index	Index	UNDP (2001).	0.596	0 – 0.77
Vegetation dummy: Puna	Dummy	Derived from Ibisch et al. (2003). Ecoregions and ecosystems map of Bolivia.	0.124	0 – 1
Vegetation dummy: Cerrado	Dummy	Derived from Ibisch et al. (2003). Ecoregions and ecosystems map of Bolivia.	0.101	0 – 1
Vegetation dummy: Amazon forest	Dummy	Derived from Ibisch et al. (2003). Ecoregions and ecosystems map of Bolivia.	0.151	0 – 1
Net present value of Net agricultural value	$/ha	Adapted from Naidoo & Iwamura (2007).	854.581	0.0033 – 2174
Natural logarithm of net present value of net agricultural value	ln ($/ha + 1)		5.773	0.0033 – 7.685

A necessary condition for deforestation to potentially take place is that there was at least some forest present in the pixel at the beginning of the period. Therefore, all the pixels with no forest cover at all in 2001 were excluded from the regression analysis. This left 92,715 pixels with positive forest cover in 2011, which were used to estimate the deforestation model (see Table 2). With over 90,000 observations and only 23 potential explanatory variables, there was no risk of overfitting, so we initially included all potential explanatory variables, but subsequently excluded those that were not found to be statistically significant at the 5% level.

Table 2: Poisson Deforestation Model for Bolivia, 2001-2005

Dependent variable	**Number of observations**	**Pseudo R^2**
Forest loss between 2001 and 2005	92,715	0.3241
Explanatory variables	**Coefficient**	**Z-value**
Initial forest cover in 2001	-1.2618	-34.42
Distance to road	-0.0143	-16.38
Distance to river	-0.0114	-11.60
Distance to urban center with more than 10.000 inhabitants	-0.0113	-27.44
Average slope of pixel	-0.0535	-21.10
Average altitude	0.0003	6.50
Carbon contents in vegetation	-0.0017	-7.61
Carbon contents in soil	-0.0043	-5.56
Net Primary Productivity	0.0265	21.71
Fire density	0.1991	30.53
Population density	0.0001	2.64
Distance to already deforested pixel	-0.2581	-10.99
Individual land title	0.1867	6.59
Communal land title	-0.6079	-13.08
Public land	-0.6644	-12.51
Human Development Index	-0.2447	-4.43
Vegetation dummy: Puna	-15.8405	-34.69
Vegetation dummy: Cerrado	-0.2522	-7.38
Natural logarithm of net present value of net agricultural value	0.0745	5.01
Constant	-1.2165	-10.40

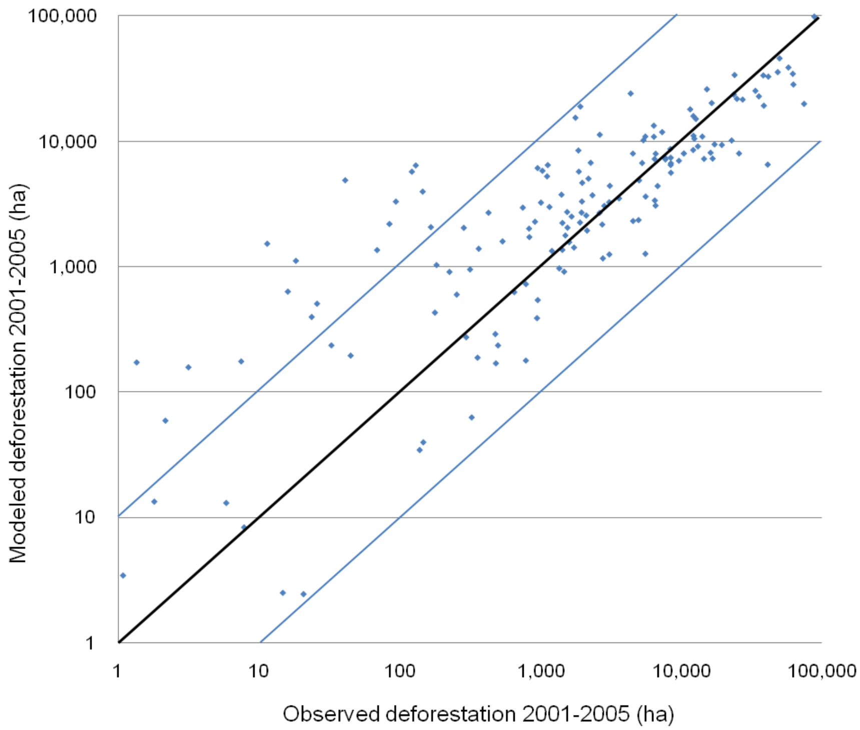
This regression model indicates that deforestation rates were higher in pixels with lower initial forest cover. This makes sense, as fragmented forest is easier to deforest than intact, dense forest. Also, as expected, deforestation rates were higher on flat areas close to roads, rivers and urban centers and close to already deforested pixels. Areas with individual, private land titles were more likely to be deforested than areas with communal land titles (Indigenous Territories (TCOs) or public land (which includes protected areas). Deforestation rates were also higher in areas with higher population density, with higher net primary productivity and with higher fire density.

Importantly, deforestation rates were higher in areas with higher agricultural value. This is important for OSIRIS, as the impact of REDD incentives is simulated through this particular variable. For example, as overall deforestation is reduced, the price of agricultural output at the frontier increases, which causes an increase in agricultural value and thus an increase in the probability of deforestation.

The explanatory power of the regression model is $R^2 = 0.32$, indicating that there is still a lot of unexplained variation in deforestation rates, even after controlling for so many factors. However, if we aggregate the results to the municipal level (337 municipalities), the correlation between measured and modeled deforestation is 0.87, which is quite high. Thus, the model is better at predicting how much deforestation will occur in a municipality than predicting exactly where within a municipality that deforestation will occur.

Figure 1 compares observed and modeled deforestation between 2001 and 2005 for every municipality with positive deforestation. The figure is presented on a log-log scale so that both small and large values are visible. The black 45° line represents the set of points at which modeled deforestation is equal to observed deforestation within a municipality. Few municipalities fall directly on the line. The blue lines indicate the boundaries within which modeled deforestation is within a factor of ten from observed deforestation. Notice that the model is substantially more accurate for municipalities with high levels of deforestation (more than 1000 ha) than for municipalities with low levels of deforestation (less than 1000 ha).

Figure 1: Observed and modeled deforestation aggregated to the municipal level, Bolivia, 2001-2005.



Source: OSIRIS-Bolivia v. 2.0.

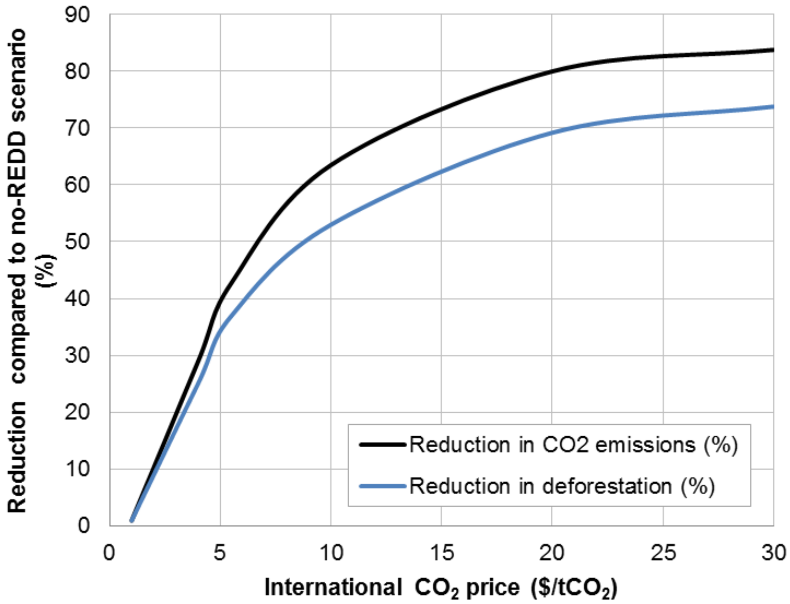
4. Applications

This section applies the OSIRIS-Bolivia tool to questions that are important for the design and implementation of payments to reduce emissions from deforestation in Bolivia. One crucial question for policy makers is how much it would cost to reduce deforestation in Bolivia by a given amount. The answer to this question will help us understand how large a reduction in deforestation we can realistically expect. Another question of considerable interest for policy makers and potential beneficiaries of the mechanism is where in Bolivia payments might most effectively reduce deforestation emissions. Additional questions explored in this section concern the role of reference levels, accounting scale, transaction costs, and preferences for agricultural income versus REDD payments.

4.1 What would it cost to reduce deforestation in Bolivia?

Several studies have claimed that reducing deforestation would be a relatively cheap way of reducing carbon emissions (e.g. Stern 2006; Antorini & Sathaye 2007; Naucler & Enkvist 2009). Other studies have proposed that on-the-ground costs may be considerably higher than suggested by top-down global models (Gregersen et al. 2010; Murray et al. 2009). OSIRIS-Bolivia lets us evaluate how large a reduction in deforestation might be achieved at alternative carbon prices. For a modest international CO_2 price of \$5/tCO_2, deforestation in Bolivia could be reduced by approximately 35% (assuming no transaction costs). At a price of \$10 it could be reduced by about 53% and at \$30 by about 74% (see Figure 2). Notice the diminishing marginal effect of increasing the CO_2 price.

Figure 2: International CO_2 price and reductions in deforestation and CO_2 emissions in Bolivia (without transaction costs)



Source: OSIRIS-Bolivia v. 2.0. (All parameters other than international CO_2 price were held constant at the default levels listed in the Appendix, except the revenue sharing parameter, which was adjusted to assure that the Central Government surplus is kept close to zero[16]).

Reducing deforestation in Bolivia becomes increasingly expensive at higher levels. Figure 3 shows that to reduce deforestation by 25% through REDD incentive payments, the international community would have to pay Bolivia about \$200 million per year, while a reduction of 50% would require more than \$700 million per year in gross REDD payments. The latter corresponds to 8.5% of Bolivia's total GDP and more than two thirds of its agricultural GDP during the period analyzed[17], so it would have a significant effect on the economy and on the distribution of income within the country.

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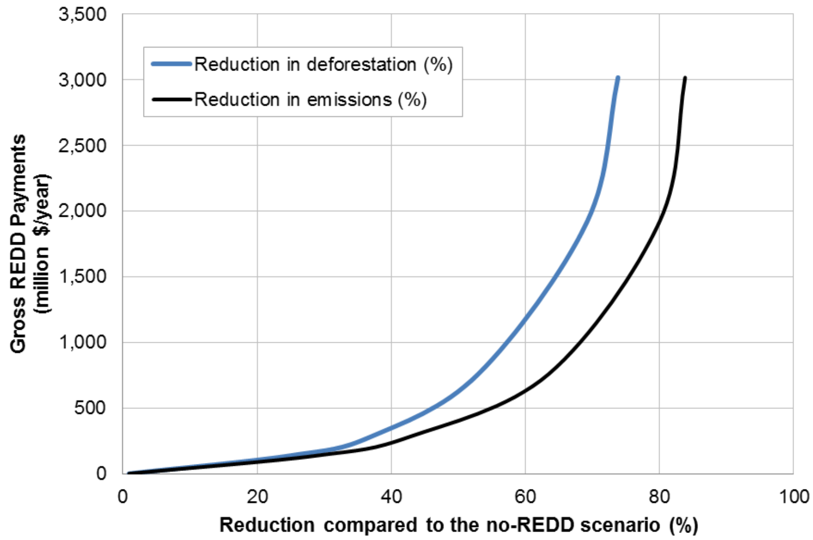
[16] If there were no leakage problem, the central government could pass on the full incentive directly to the participating land owners, but when there is leakage, the central government needs to retain some of the revenues to cover the reduced compensation due to leakage. In all simulations in this paper, we have made sure to adjust the revenue sharing parameter so that there is no impact on central government finances.

[17] According to the National Statistical Institute (www.ine.gob.bo) total annual GDP was fluctuating around \$8.3 billion during this period while agricultural GDP amounted to about \$1.1 billion per year.

Figure 3: Reductions in deforestation and CO_2 emission versus gross annual REDD payments



Source: OSIRIS-Bolivia v. 2.0. (All parameters other than international CO_2 price were held constant at the default levels listed in the Appendix, except the revenue sharing parameter, which was adjusted to assure that the Central Government surplus is kept close to zero).

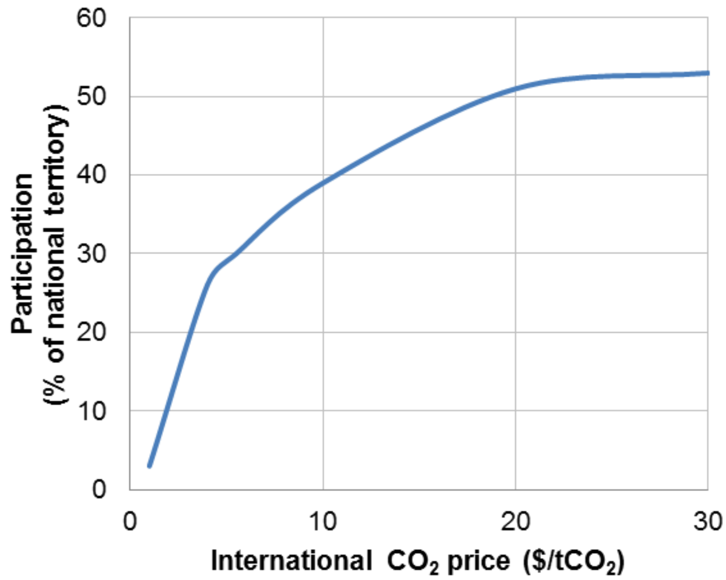
4.2 Where in Bolivia might REDD work?

There are three main conditions that make an area more likely to participate in a standard REDD mechanism paying for reduced emissions from deforestation:

- Higher initial forest carbon stock
- Higher deforestation rates in the reference scenario
- Ability to reduce to low deforestation rates more cheaply

For each site/municipality, OSIRIS-Bolivia compares the potential net income from agriculture and carbon from opting into REDD with the potential net income from opting out of REDD, based on a given reference level and CO_2 price. Map 1 indicates the pixels where potential REDD income would be higher than potential agricultural income if the CO_2 price is set at $5/t$CO_2$ and the reference level is business-as-usual. The higher the CO_2 price, the more pixels would be interested in participating in the REDD mechanism. Figure 4 shows how participation in REDD depends on the international price of CO_2. Participation increases steeply as the price increases toward $5/t$CO_2$, but further increases produce only limited increases in participation. At a price around $20/t$CO_2$ almost all forested pixels (56% of the national territory) would wish to participate in the mechanism, and further price increases would cause little additional participation.

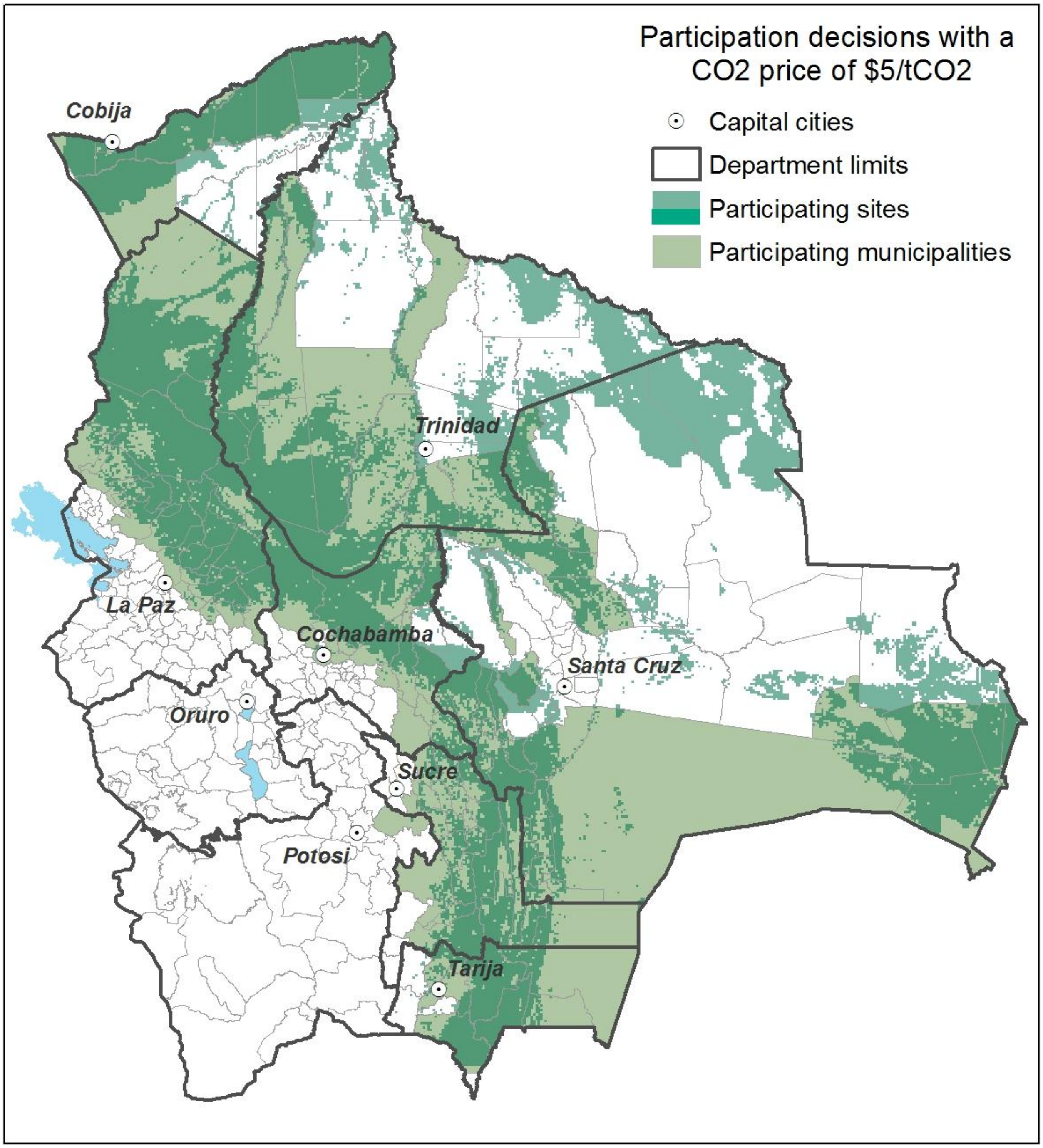
Figure 4: International CO_2 price and pixel level participation in the REDD mechanism



Source: OSIRIS-Bolivia v. 2.0. (All parameters other than international CO_2 price were held constant at the default levels listed in the Appendix, except the revenue sharing parameter, which was adjusted to assure that the Central Government surplus is kept close to zero).

The REDD mechanism can be set up to work with either private land holders at the site level, or administrative units like municipalities. If REDD is implemented at the municipal level, it means that REDD revenues would be paid to the municipality, instead of directly to the individuals, and the municipality would decide how to distribute/invest the revenues so as to reduce deforestation and benefit the local population. Map 1 indicates which sites/municipalities would benefit from participating in REDD as potential REDD revenues would surpass potential net agricultural benefits at the site/in the municipality (for a CO_2 price of \$5/tCO_2).

Map 1: Sites/Municipalities which might participate in a REDD scheme with a CO_2 price of \$5/tCO_2 and a business-as-usual reference level.



Source: OSIRIS-Bolivia v. 2.0 (All parameters at default values, except CO_2 price was set at \$5/tCO_2 and both site level and municipality level decision making were set to 1.)

The Bolivian Altiplano in the southwest is effectively excluded from REDD because of its lack of forest and resulting lack of deforestation. Much of the department of Santa Cruz in the east, where observed deforestation is most intense, appears unlikely to participate in REDD because of high opportunity costs. The areas that show most potential for REDD are the lowland regions of the department of La Paz, the department of Pando in the north, the department of Tarija in the south, and the far eastern part of the department of Santa Cruz.

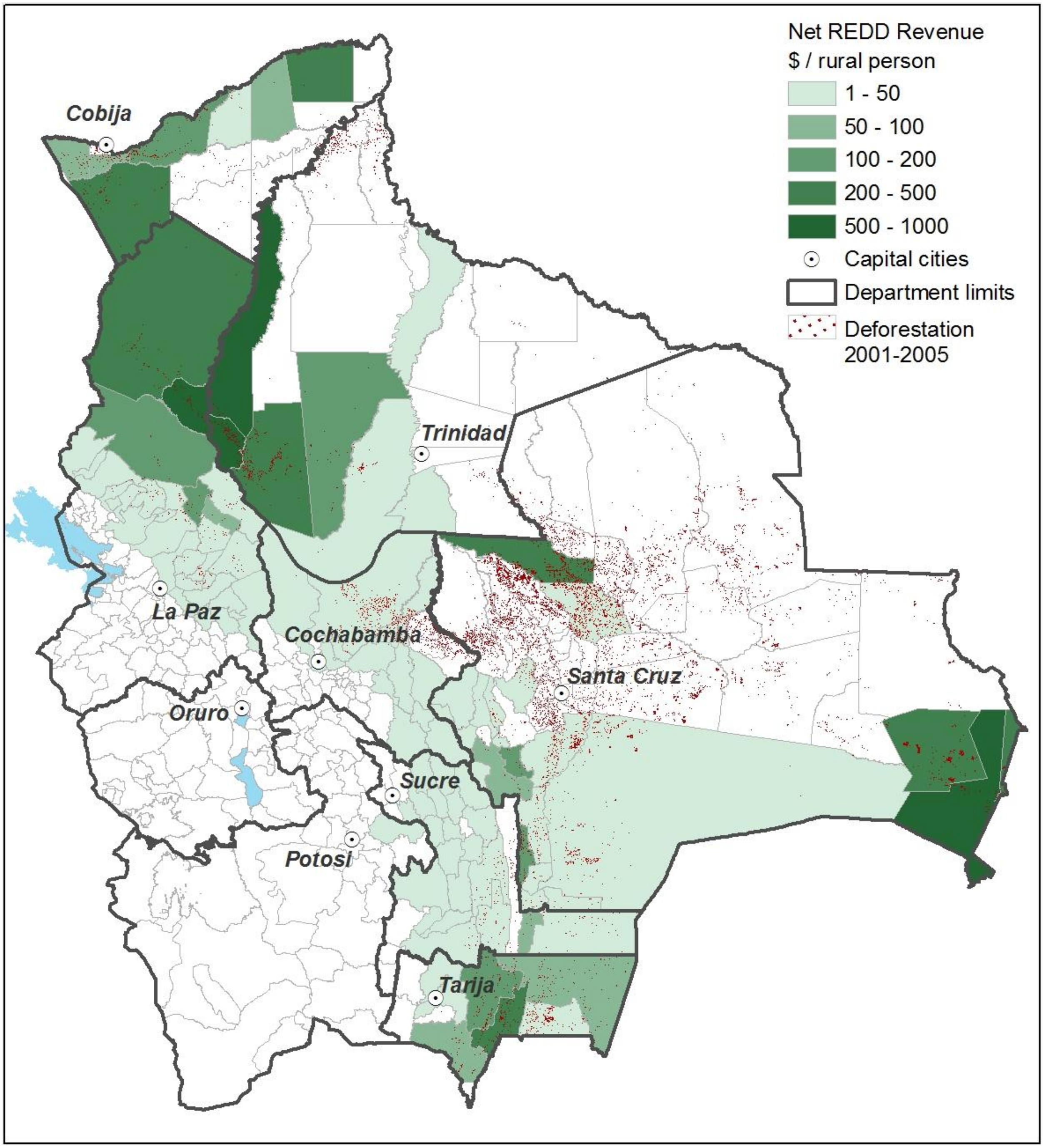
4.3 Who would benefit most from participating in REDD?

Since the Bolivian government is officially opposed to carbon emissions trading, the default parameters in OSIRIS-Bolivia are set up to analyze the impacts of a $1 billion external donation to reduce deforestation over the four year period analyzed. Thus, in the remaining simulations in this paper, rather than fixing the carbon price, we fix total gross REDD Payments at $1 billion. This is a convenient number and it reflects the magnitude of financing necessary to substantially reduce deforestation in Bolivia. It allows us to answer the question "What can $1 billion of REDD financing achieve in Bolivia in terms of reduced emissions and increased rural incomes?" and allows us to compare this with $1 billion spent in different ways in Bolivia or in similar ways in other countries.

How much each municipality would benefit from participating in REDD on a per-capita basis depends not only on CO_2 prices, reference levels and opportunity costs, but also on the population of the municipality.

One of the key outputs from OSIRIS-Bolivia is Net Revenue Advantage from opting into REDD, which is calculated as the gross REDD revenues received from reduced emissions minus forgone agricultural revenues minus transaction costs. Given that REDD is mostly relevant for the rural population, we have mapped net REDD revenues per rural person in Map 2.

Map 2: The distribution of net REDD revenues per-capita across the rural population of Bolivia, with $1 billion in gross REDD payments and a business-as-usual reference level. Emissions reductions achieved: 189 million tCO_2.



Source: OSIRIS-Bolivia v. 2.0 (All parameters at default values).

The areas that show the highest net REDD revenues are the lowland part of the department of La Paz, the department of Pando in the north, the department of Tarija in the south, and the far eastern part of the department of Santa Cruz. In these regions carbon stock and deforestation are high, the opportunity cost of maintaining forest is low, and the rural population is low, so the revenues are shared between relatively few people. According to this simulation, four municipalities would experience net REDD revenues above $500 per rural person per year (San Buenaventura, Reyes, Rurrenabaque and Puerto Suarez). The highest benefit found is $710 per rural person per year (in San Buentaventura), which is high relative to the average rural income in rural municipalities of around $300 per person per year[18].

It is important to point out that participation and benefits from REDD depend crucially on how the national incentives for REDD are structured, including how domestic reference levels are set. The benefit map can look quite different if a different method for setting the domestic reference levels is chosen (see next sub-section).

4.4 The importance of the choice of reference levels

Establishing reference levels, or the baseline below which reductions in emissions from deforestation would be credited, is one of the most critical elements of REDD policy design (Busch et al. 2009). Under an international REDD mechanism, national reference levels would be determined in international negotiations, however, countries would be free to create their own national policies to reduce domestic emissions from deforestation (Busch et al. 2012). In other words, the national baseline below which Bolivia would receive payment from the international community for emissions reductions will be determined at the international level, but Bolivia can use this money to reduce emissions from deforestation within its borders in whatever way it sees fit. Therefore, one of the important choices when designing a national REDD policy is to determine the domestic reference levels, since this will affect how payments are distributed within Bolivia.

OSIRIS-Bolivia allows users to analyze three types of domestic reference levels: historical, business-as-usual (BAU), and combined incentives (Strassburg et al. 2009). Historical reference levels are equal to observed rates of emissions from deforestation in the department, municipality or site (depending on choice of accounting scale, explained further below). A BAU reference level refers to the level of emissions from deforestation that would occur in the department, municipality or site in the absence of a REDD mechanism. BAU reference levels may be estimated using econometric methods taking into account the drivers of deforestation (e.g. the model presented in section 3 above or non-parametric methods like the multi-layer perceptron neural network applied in Sangermano et al. (2012)), though in practice they may be difficult to estimate accurately (Busch et al., 2012). A combined incentives reference level is the weighted average of the local historical and national average historical rates. The goal of a combined incentives reference level is to incentivize the participation of regions with historically low deforestation rates while requiring a greater level of initial contribution from regions with historically high deforestation rates. This type of reference level maintains the aggregate national rate at the historical level, by setting reference levels for both types of regions closer to the national average.

The choice of sub-national reference levels has important effects on emissions reductions, the level of net benefits to the country, and the distribution of these benefits within the country. In OSIRIS-Bolivia, the BAU reference level is the most efficient in reducing deforestation because the predicted BAU level of deforestation is assumed to reflect exactly the amount of deforestation the region would have incurred in the absence of any REDD incentives. There are thus no wasted payments due to “hot air” (payments for “non-additional” reductions) due to the reference levels being set too high, and there is a minimum of avoidable non-participation from reference levels being set too low.

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[18] Average per capita consumption in Bolivian municipalities that are 100% rural, according to UNDP’s Human Development Index for 2001 (not adjusted for purchasing power parity).

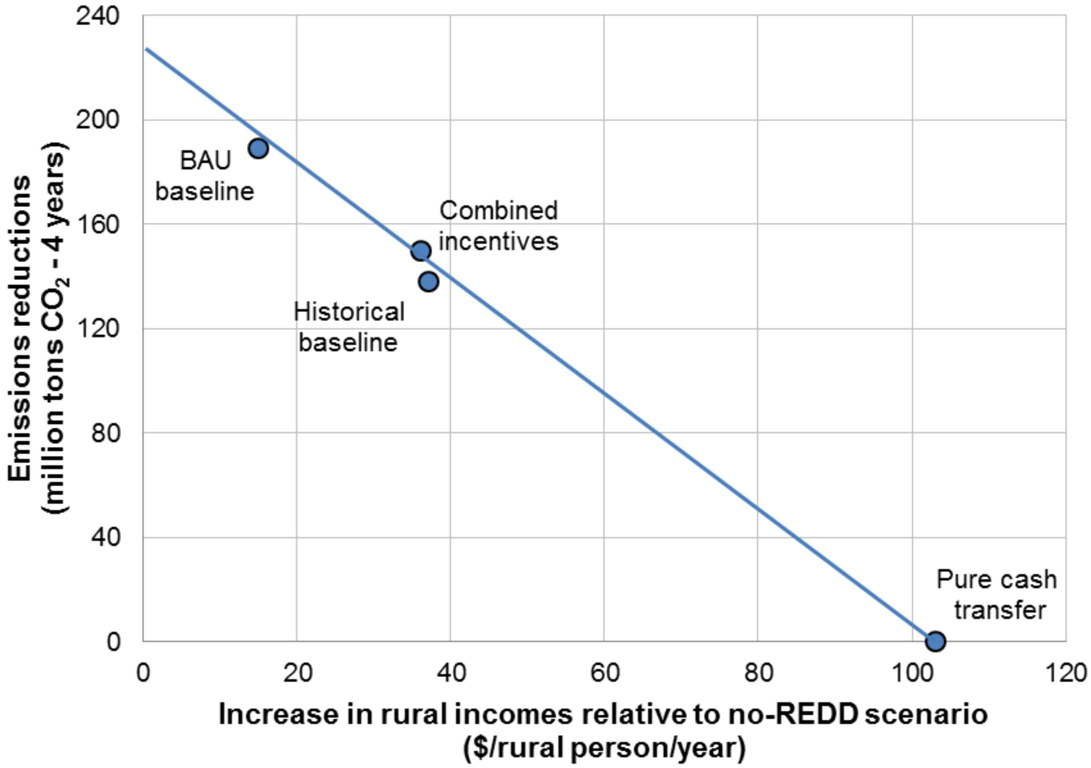
Using reference levels that deviate from future rates is less efficient. For example, purely historical deforestation rates will probably not accurately predict future deforestation rates. This is due to the fact that the agricultural frontier tends to move gradually from highly developed areas towards virgin areas (Andersen et al. 2002). This means that an area which has historically been located beyond the frontier, experiencing very low deforestation, can suddenly experience high deforestation rates during the period when the frontier is passing by. Later, this same region will stabilize and experience lower deforestation rates (possibly because there is no forest left to deforest). If the historical reference level is lower than the actual pressure to deforest, farmers in this area will choose not to participate in the REDD mechanism because they would first have to reduce emissions down to the reference level at their own expense. On the other hand, if the historical reference level is higher than the actual pressure to deforest, donors will pay for effortless emissions reductions (hot air). Reference levels based on combined incentives perform slightly better than historical reference levels in terms of decreased emissions and have the advantage of being much simpler to calculate than a BAU reference level.

If the REDD mechanism pays land owners exactly their opportunity costs in order to stop farming, then the net benefit to land owners from participating relative to not participating is zero, by definition. Positive net benefits to land owners arise when they are paid more than the opportunity costs. There are several reasons why they may receive a higher payment. First, if donors offer a fixed price for CO_2 emissions reductions, they will have to pay both land owners that have that exact opportunity cost as well as all those who have lower opportunity costs, and the latter will experience positive net benefits from participating in the mechanism. Second, it is difficult to know exactly how much land owners intended to deforest, and, if the baseline is set too high, donors will end up paying for some hot air. In general, the payment received is distributed between compensation for opportunity cost (which reduces deforestation) and rent (which increases net income).

Figure 5 shows that there is a clear trade-off between emissions reductions and rural income increases for a given amount of donor spending (in this case $1 billion for the four year period). The more efficient the mechanism is at reducing deforestation, the less the local rural population benefits in terms of increased net incomes relative to not participating, and vice versa. For comparison, we have included the outcomes of a pure cash transfer of $1 billion in equal amounts to the whole rural population over 4 years. This would increase rural per capita incomes by $103 per year (equivalent to an average increase of 34%).

The highest possible emissions reduction that could be achieved with $1 billion would be if we could perfectly ascertain the opportunity costs at each plot, rank the plots from lowest to highest opportunity cost, and make payments only to those farmers with the lowest opportunity costs. In that very hypothetical case, we could achieve emissions reductions of 402 million tCO_2 for the 4-year period. Since farmers would be paid only their opportunity costs, the increase in net REDD revenue across all farmers relative to the no-REDD scenario would be zero.

Figure 5: The trade-off between efficiency in reducing emissions and efficiency in increasing incomes of rural inhabitants in Bolivia (simulations with $1 billion in international financing and zero transaction costs).



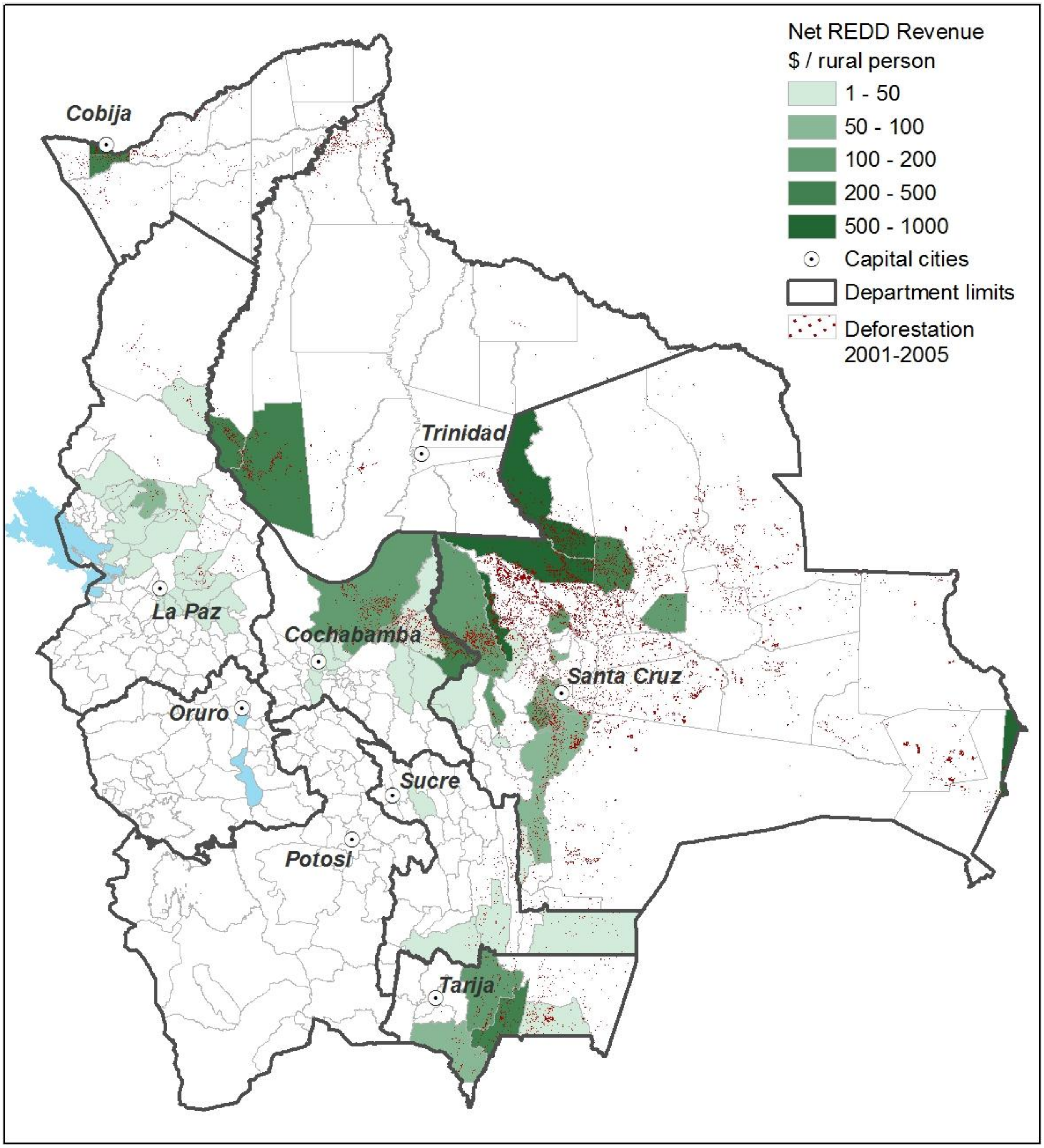
Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except the baseline type. In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

The nearly zero-sum relationship shown in Figure 5 arises only in the case of a fund of fixed size. If instead the carbon price is fixed and the fund size is variable depending on carbon emissions reduction performance, as it might be for countries participating in the carbon emissions trading market, then the distribution between rent and opportunity cost would not be a zero sum game. For example, with a fixed carbon price, a cash transfer scheme would generate total payments of $0.

Maps 3 and 4 show how different the distribution of net REDD benefits looks when the baseline is changed from business-as-usual to historical or to combined incentives.

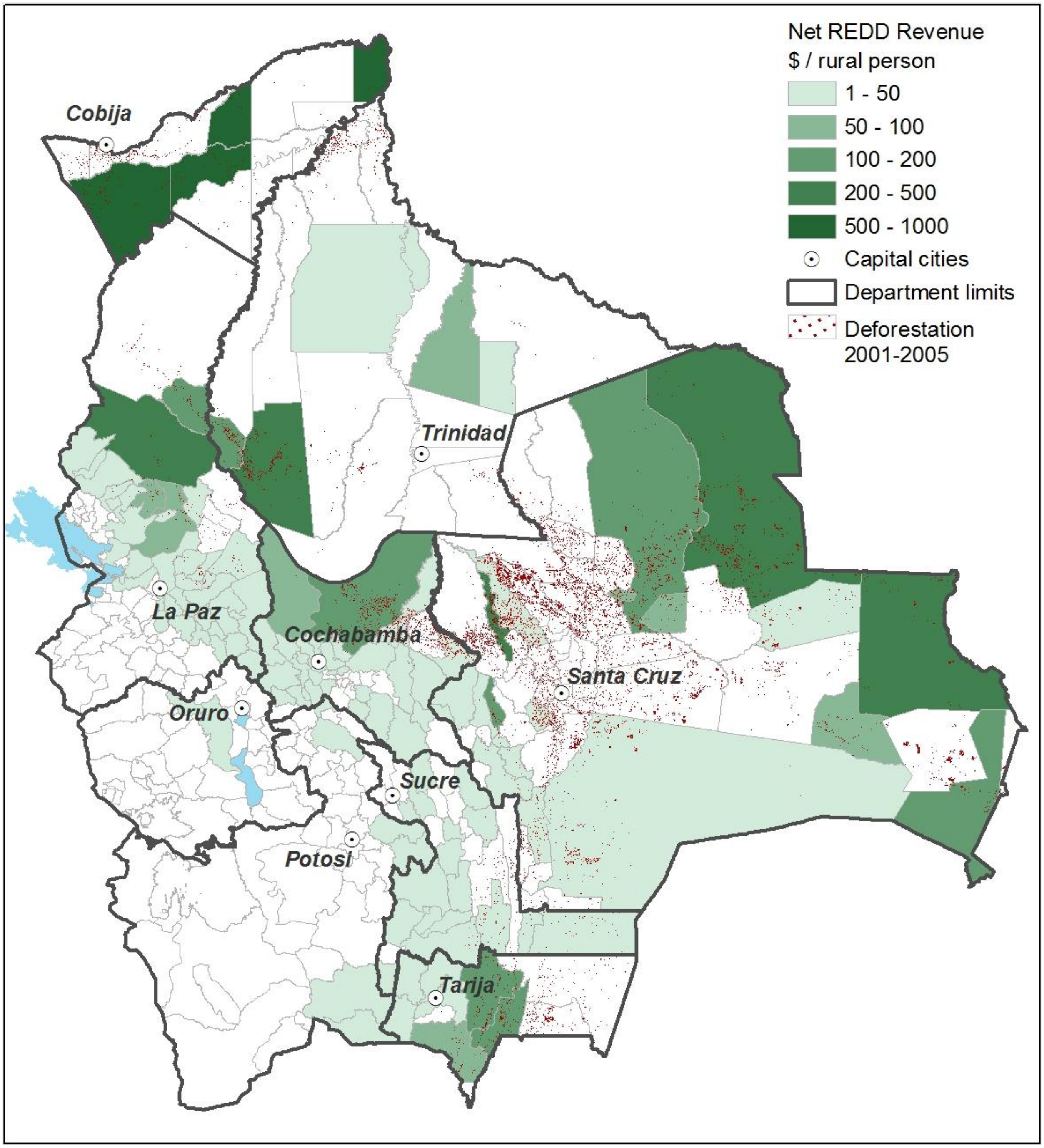
In all three cases (Maps 2, 3 and 4), the net REDD revenues are very concentrated. Even under the generous assumption of Net REDD Benefits being evenly distributed between all people within each municipality, more than 90% of the Net REDD Benefits will accrue to municipalities containing less than 5% of the population. However, since the REDD incentives target the rural population, they would still cause a very slight improvement in the overall income distribution (a decrease of 0.27 Gini points) in the best case. According to OSIRIS-Bolivia, the percentage of the rural population who would participate in the mechanism in these three cases would be 36.3%, 27.1% and 49.9%, respectively.

Map 3: The distribution of net REDD revenues across the rural population of Bolivia, with $1 billion in Gross REDD payments and a historical reference level. Emissions reductions achieved: 138 million tCO_2.



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except the baseline type, which was set to "historical". In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

Map 4: The distribution of net REDD revenues across the rural population of Bolivia, with $1 billion in gross REDD payments and a combined incentives reference level. Emissions reductions achieved: 150 million tCO_2.



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except the baseline type, which was set to "combined incentives." In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

4.5. Co-benefits

In addition to reducing deforestation and carbon emissions, REDD payments would likely also decrease biodiversity loss due to deforestation and potentially increase the income of the poor. OSIRIS-Bolivia v. 2.0 estimates these effects plus the percentage of rural population participating in the program. Figure 6 shows the results.

OSIRIS-Bolivia contains data on biodiversity at the pixel level, using the variable Absolute Species Richness estimated by Nowicki (2004). It uses 17 groups of plants and animals as taxa-indicators. The highest number of species found within these 17 groups is 2825 species per pixel[19] while the lowest is 0 (for example in glaciers and salt flats).

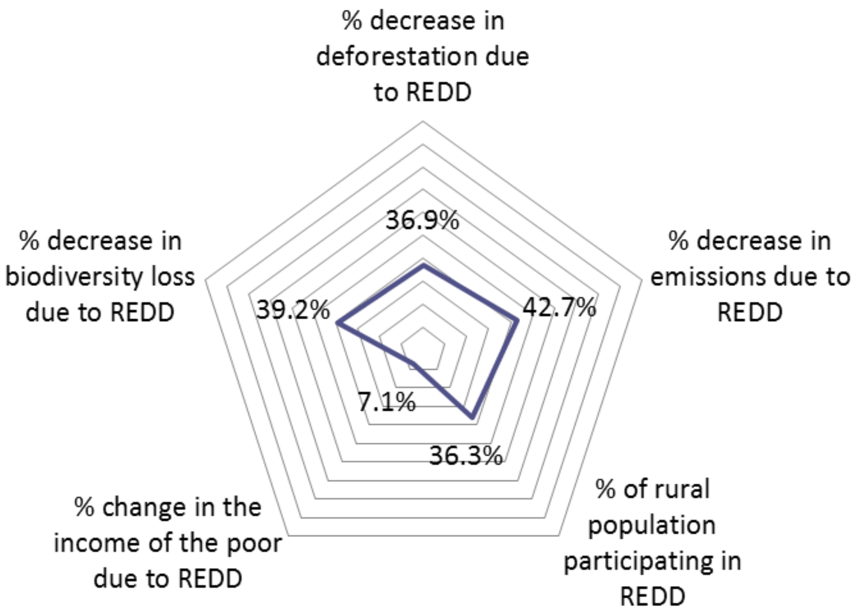
OSIRIS-Bolivia estimates the effect of REDD on biodiversity by calculating the reduction in the loss of biodiversity-habitat compared to the no-REDD scenario. Thus, saving 1 hectare of habitat with an Absolute Species Richness level of 1000 would be equivalent to saving 2 hectares of habitat with Absolute Species Richness of 500.

In the default scenario of $1 billion in international financing and using a business-as-usual reference level, OSIRIS-Bolivia shows a decrease in biodiversity-habitat loss of 39.2%. This is slightly more than the decrease in deforestation of 36.9%, indicating that the mechanism tends to target areas with above average biodiversity, although this is not an explicit criterion for REDD.

Data on per capita income is available only at the municipal level in OSIRIS-Bolivia. By setting a poverty line of $2 per day, OSIRIS-Bolivia calculates a 7.2% increase in the per capita income of poor municipalities that opt into REDD. The average increase in per capita income across all poor municipalities is 2.2%.

[19] The pixels used in Nowicki (2004) are slightly larger than the pixels in OSIRIS (3.6 by 3.6 km rather than 3 by 3 km) so the data was resampled to fit the OSIRIS pixels.

Figure 6: REDD benefits and co-benefits



Source: OSIRIS v. 2.0 (All parameters at default values).

4.6. The role of transaction costs

So far we have not included the role of implementation and transaction costs of REDD. In reality the financial resources needed to develop the technical and institutional capacity required to launch a functioning REDD mechanism are likely to be substantial (Pagiola and Bosquet 2009). Implementation costs include those for technical and institutional capacity building (often referred to as REDD readiness) as well as actions to reduce deforestation that are not directly related to payments for emissions reductions, such as establishing clear property rights and investing in programs to improve agricultural efficiency on already deforested land. Transaction costs are "the resources used to define, establish, maintain and transfer property rights" (McCann et al. 2005). This definition recognizes that environmental goods and services often lack clear definition, and that in addition to costs associated with negotiating and executing a payment, the costs needed to build institutional capacity and establish explicit property rights should also be included.

The OSIRIS-Bolivia model separates initial costs, such as those for developing technical and administrative readiness, from the transaction costs of negotiating, executing and monitoring REDD payments. Initial costs are a fixed input parameter that is borne by the national government or international institutions. In the model they are simply subtracted from gross national revenue from REDD payments along with forgone agricultural revenue and transaction costs to calculate Bolivia's net revenue from REDD. In reality, Bolivia is likely to rely on international funding to cover most of these start-up costs. The default value for start-up costs is set at 0 in OSIRIS-Bolivia.

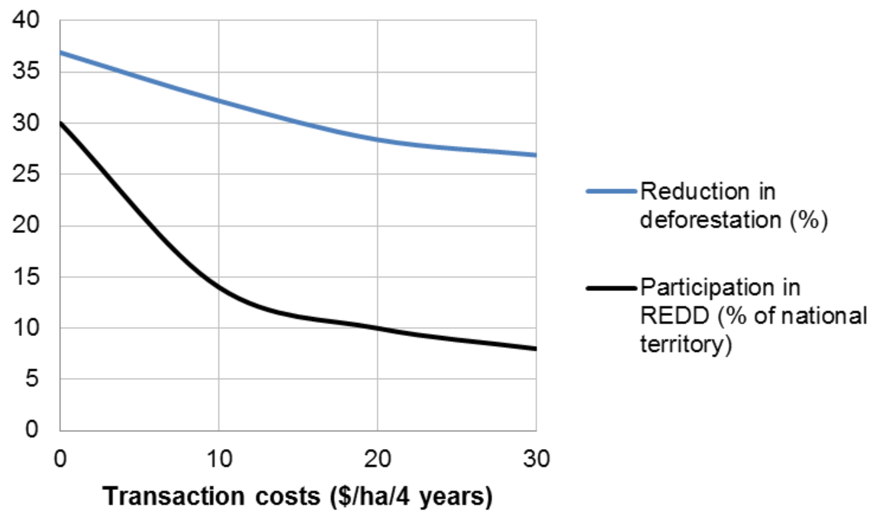
OSIRIS-Bolivia also allows a fixed input parameter of a transaction cost per hectare/4 years. This transaction cost is then subtracted from the would-be gains from carbon payments from opting into

REDD and, therefore, included in the decision of site, municipalities or states to opt-in or out of the REDD mechanism. Transaction costs have a direct effect on participation rates and consequently affect reductions in deforestation and emissions. Higher transaction costs reduce the number of actors choosing to participate by increasing the opportunity cost of participation.

The Stern Review, which includes analysis of tropical forests in Bolivia, estimates transaction costs ranging from $5 to $15 per hectare (Grieg-Gran 2006). In Bolivian REDD, the Noel Kempff Climate Action Project incurred transaction costs of $3.3 million for a 634,286 hectare project (Antorini & Sathaye 2007), corresponding to $52/ha. Dividing those costs over the first 10 years of the project produces a cost around $5.2 per hectare per year, or approximately $20 per hectare per 4-year period.

In Figures 7 and 8 we show the impacts of transaction costs in the range from $0 to $30 per hectare per 4 year period. Participation decreases sharply when transaction costs are added, as the areas with opportunity costs close to the international carbon price (in this simulation $5.5/tCO_2$) drop out, but the reduction in deforestation decreases less sharply.

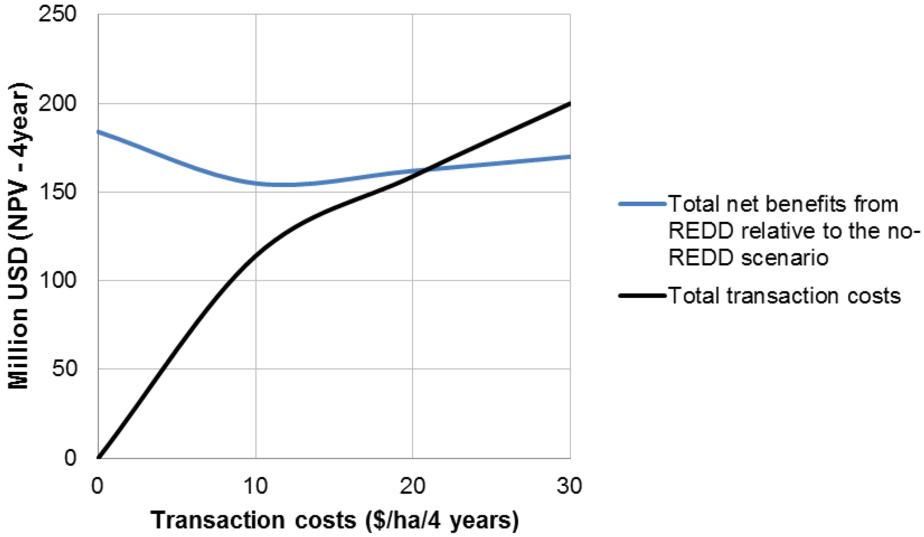
Figure 7: The impact of transaction costs on REDD participation and deforestation reductions (simulations with $1 billion in international financing).



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except transaction costs. In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

Figure 8 shows that total transaction costs increase rapidly to about $200 million per 4-year period (20% of total financing) if transaction costs reach $30/ha/4years. This is very close to the 19% of total costs of the Noel Kempff Climate Action Project (Antorini & Sathaye 2007). In contrast, Net REDD Benefits are hardly affected because it is the sites with close to zero net benefits which drop out when transaction costs are introduced and instead the $1 billion in external financing is concentrated on paying a higher price to fewer plots resulting in higher increase in net benefits relative to the no-REDD scenario.

Figure 8: The impact of transaction costs on increase in net REDD Benefits relative to the no-REDD scenario (simulations with $1 billion in international financing).



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except transaction costs. In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at 1 billion at the same time as the Central Government surplus remained close to zero).

Transaction costs thus tend to be borne mainly by the donors. With transaction costs in the range of 20% of total financing, deforestation reductions are going to be about 27% lower than if there were no transaction costs, while the increase in net REDD benefits for Bolivia is only going to be 8% lower.

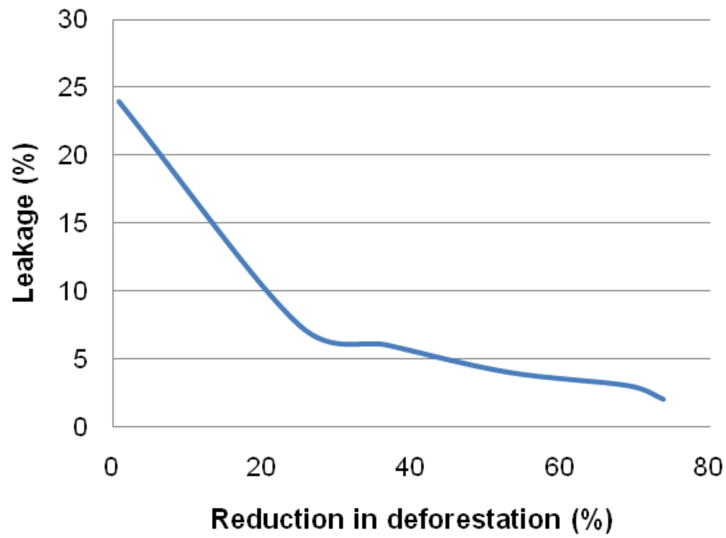
The incidence of transaction costs upon the donors holds for a fixed fund size as analyzed in this paper. However, for a carbon market situation where the price of carbon emissions reductions are held constant instead of the overall amount of funding, transaction costs would mainly be borne by the host country, as the net benefit from REDD decreases substantially as transaction costs increase.

4.7. Leakage

Efforts to reduce deforestation face the problem of leakage, in which a reduction in deforestation in one location increases agricultural prices, increasing pressure to deforest in other locations. High levels of leakage reduce the effectiveness of actions to diminish overall deforestation emissions. In OSIRIS-Bolivia, leakage is measured as the volume of local increases in emissions as a fraction of the volume of total gross reductions in emissions.

The relative level of leakage as deforestation is reduced is not predicted by theory. On one hand, the higher the increase in agricultural prices, the higher the incentive for increasing deforestation. The strength of this effect is determined mainly by sensitivity of domestic production price to changes in deforested area. On the other hand, as payments to reduce deforestation incentivize participation more broadly, less forest area remains for potential leakage. As indicated by Figure 9, the latter effect tends to dominate in OSIRIS, so that leakage is lower for high reductions in deforestation.

Figure 9: Estimated leakage at different levels of reduced deforestation



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except the revenue sharing parameter and the international CO_2 price which were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

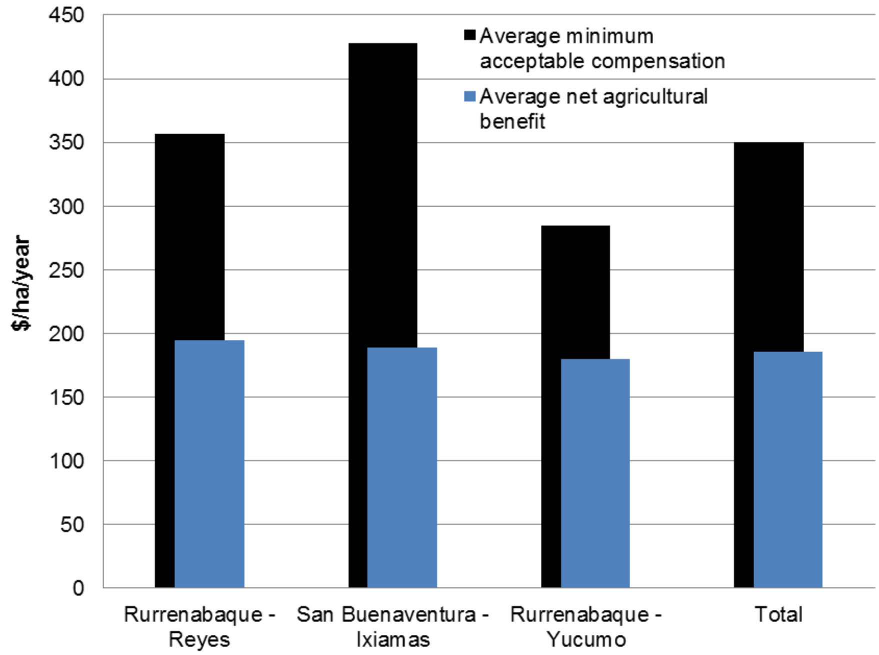
Sohngen & Brown (2004) estimated the leakage for the Noel Kempff Climate Action Project to be in the range 2 – 40%. The middle of this admittedly wide interval corresponds quite well to the predictions of OSIRIS for low levels of reduced deforestation.

4.8. Preferences for agricultural revenue relative to REDD+ revenue

We initially assumed that a dollar of income from carbon payments would have an equal and opposite impact on deforestation as a dollar of income from agriculture. However, concerns about food security or unfamiliarity with the REDD+ mechanism might imply that farmers prefer continuing agriculture over equal income from forest conservation, justifying a parameter value of $\gamma > 1$. There are also arguments that might justify γ being less than one. For example, farmers may be able to use the time they have freed up to engage in other types of productive activities, thus earning not only the REDD+ payments, but also alternative non-agricultural income. They may have a preference for leisure rather than agricultural work, or may derive value from the ecosystem services provided by forests.

An empirical study designed to establish conservation opportunity costs in Bolivia found that farmers, when asked about the minimum compensation they would need to give up agricultural activities on a certain plot, demanded an annual compensation for conservation that was on average almost twice as high as their net agricultural revenues from that plot (see Figure 10) (Leguia, Malky & Ledezma, 2011). This could be because farmers tend to underestimate their labor costs and thus overestimate their net revenues, but it could also be because they have a strong preference for familiar agricultural revenues, self-sufficiency and food security, compared to uncertain and unfamiliar REDD payments.

Figure 10: Comparison of stated net agricultural revenues and minimum compensation payments, on different stretches of road in North-western Bolivia.

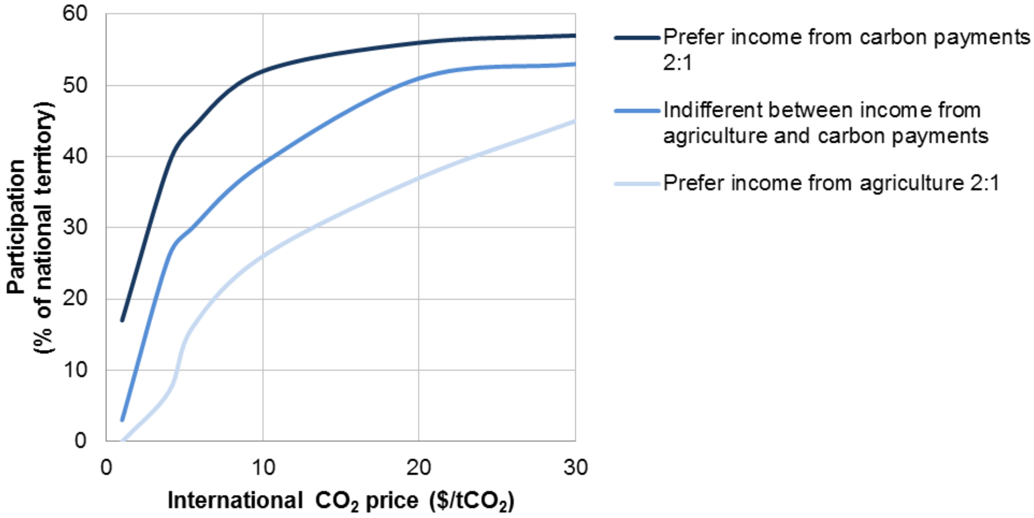


Source: Leguia, Malky & Ledezma (2011).

OSIRIS-Bolivia allows the user to investigate the effects of alternative preferences for agricultural income versus REDD income. Figure 11 shows that participation in the REDD mechanism would be substantially lower if actors have a 2:1 preference for agricultural income rather than REDD payments, especially at low CO_2 prices. For example, at a price of \$5/tCO_2, participation would be 16% rather than 30% if people require \$2 of REDD payments to compensate for \$1 of agricultural net revenue. However, at high CO_2 prices, even actors with a strong preference for agricultural income would decide to participate in the REDD mechanism.

On the other hand, if actors preferred REDD payments to agricultural income by a factor of 2:1, then participation would be 45% even at the relatively modest price of \$5/tCO_2.

Figure 11: Participation depends on the preferences for agricultural income versus income from carbon payments.



Source: OSIRIS-Bolivia v. 2.0. (All parameters at default values, except the preference parameter. In addition, the revenue sharing parameter and the international CO_2 price were adjusted to assure that gross REDD payments stayed at $1 billion at the same time as the Central Government surplus remained close to zero).

5. Conclusions and recommendations

The international REDD mechanism is still in the phase of design and negotiation. Quantitative information is needed to guide the process toward a mechanism that is fair and effective and which will receive sufficient funding to significantly reduce deforestation.

OSIRIS-Bolivia attempts to help fill the current quantitative information gap. It is based on several million data points of social, economic and environmental information. The simulations shown in the present paper allow us to draw a number of noteworthy policy conclusions concerning the social and economic impacts of a mechanism designed to compensate people for reducing emissions from deforestation.

First, the amount of international financing needed to reduce deforestation in Bolivia is likely to be very large. In a relative sense, it may be cheaper to reduce deforestation in Bolivia than to reduce emissions in rich countries, but in absolute terms hundreds of millions of dollars of international financing are required each year in order to meaningfully reduce deforestation through a REDD mechanism. According to OSIRIS-Bolivia it would have required at least $700 million per year in gross REDD payments to reduce deforestation by 50% during the 2001-2005 period. For comparison, Bolivia's agricultural exports averaged less than $100 million per year in the same period. Still, according to the simulations, this level of funding would have resulted in emission reductions of 65 million tCO_2/yr (almost twice the total annual emissions of Norway), at the relatively low carbon price of $9/$tCO_2$.

Second, the benefits arising from these international transfers are likely to be extremely concentrated. Both the urban population and the rural population in the Bolivian highlands with little forest and hardly any deforestation are naturally excluded from a mechanism focused on compensating reduced emissions from deforestation. Even within the forested lowlands, benefits would be unevenly distributed because deforestation in the reference scenario is unevenly distributed. Overall, the results show that municipalities containing less than 5% of the population would receive more than 90% of the increase in net revenues (gross carbon payments minus forgone agricultural revenues) from REDD relative to the no-REDD scenario. In addition, the distribution of these revenues could have an uncertain or arbitrary component, depending on the methods by which reference levels are assigned. Thus, if REDD were to be implemented in Bolivia, considerable effort should be made to improve the distributional effects, possibly sacrificing some environmental efficiency to ensure acceptable distributional outcomes.

Third, agricultural prices could be sensitive to reductions in agricultural production, so it is important that at least a part of the REDD payments gets directed towards improving agricultural productivity on already cleared land. Some investments in agricultural intensification may naturally result through market feedbacks as newly cleared agricultural land becomes scarcer, but this process can be proactively facilitated through technical assistance and policies that encourage agriculture on previously deforested lands.

Fourth, leakage diminishes as participation in REDD is broadened. Leakage is potentially a serious problem unless the REDD mechanism is implemented nationwide. Most farmers in the Bolivian lowlands are either migrants or descendants of migrants, so they have a high level of mobility and a geographically extended family network. Thus, farmers could potentially participate in a REDD mechanism in one area, while using the revenues to expand their agricultural activities in another. This means that the effectiveness of a REDD mechanism in Bolivia could be undermined if it is not implemented consistently at a national scale.

Although OSIRIS-Bolivia is based on massive amounts of data, it is still only a simplified economic model and should be used only with its limitations in mind. It focuses exclusively on positive economic incentives for reducing deforestation, but the actual outcomes would depend on the overall policy environment in which these incentives are implemented. For example, positive incentives will likely be much more effective if combined with effective control and fines for illegal deforestation, whereas they would be much less effective in the presence of contradictory policies promoting the expansion of the agricultural frontier. Entirely external factors, like the evolution of world food prices, could also easily have a larger effect on deforestation than the positive incentives simulated in OSIRIS.

The simulations in OSIRIS-Bolivia are focused on paying land owners or municipalities for carbon emissions reductions below an established baseline. In reality, however, it may be impractical and costly to establish reference levels for individual land owners and certify their emissions reductions in order to pay the right compensation. Furthermore, the results of OSIRIS-Bolivia show that the distribution of benefits under such a mechanism can be highly concentrated. Simpler mechanisms that do not require elaborate reference levels and costly carbon accounting may be more likely to be successfully implemented on a large scale. Costa Rica's PES scheme (Rodríguez-Zúñiga 2003) and Ecuador's Socio Bosque program (Koning et al. 2011) are examples of much simpler mechanisms involving long-term conservation contracts that yield semi-annual payments to land-owners. Future research should involve the extension of OSIRIS-Bolivia to analyze these types of conservation incentives, so that the multidimensional outcomes of the different types of incentives can be properly compared.

Finally, it should be noted that the data used for OSIRIS-Bolivia is already about a decade old, and conditions may have changed recently. Thus, the analysis should be updated as new census data and deforestation data become available.

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Appendix: List of default values in OSIRIS-Bolivia v. 2.0

Name	Value
World carbon price ($/tCO2e)	$5.50
Bolivia national reference level as proportion of BAU emissions:	1.00
Revenue sharing: portion of world carbon price withheld by national government of revenue for emission reductions below reference level	0.07
Cost sharing: portion of cost borne by national government for emission increases above reference level	1.00
Reference level design: Basis for reference level -- 1 = historical; 2 = predicted BAU; 3 = "combined incentives"	2
State reference level as proportion of provincial BAU	1.00
Municipality reference level as proportion of district BAU	1.00
Site-level reference level as proportion of site-level BAU	1.00
State reference level floor, as proportion of average national emission rate	-
Municipal reference level floor, as proportion of average national emission rate	-
Site-level reference level floor, as proportion of average national emission rate	-
Combined incentives: state reference level's weight on national historical emission rate vs. state historical emission rate	0.50
Combined incentives: municipal reference level's weight on national historical emission rate vs. municipal historical emission rate	0.50
Combined incentives: site reference level's weight on national historical emission rate vs. site historical emission rate	0.50
Eligibility for participation in REDD+	1
National accounting	1
State level accounting	-
Municipality level accounting	1
Site level accounting	-
Soil percent included in emission factor	0.1
Social preference for agricultural surplus relative to REDD surplus -- Default = 1.00	1.0
Sensitivity of domestic production price to change in deforested area	1.4
Exogenous increase in agricultural price (from decrease in global agricultural area e.g. due to global REDD+ mechanism)	0.0
Start-up costs ($; NPV)	$0
Transaction costs per hectare ($/4yr)	$0