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Assessing the influence of land-cover change and conflicting land-use authorizations on ecosystem conversion on the forest frontier of Madre de Dios, Peru

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ABSTRACT

Despite the many benefits natural forests provide, they are being lost worldwide at unsustainable rates as development frontiers expand. One approach to improving the efficacy of natural forest conservation efforts is to refine local forest conservation policies based on insights from the place-based study of conservation policies and land-use and land-cover change (LULC) dynamics. To demonstrate the strength of this approach, this research explores the dynamics of LULC and conservation policies on the forest frontier of Madre de Dios, Peru. The main objectives of this research are to evaluate the efficacy of designated conservation lands in a rapidly expanding frontier landscape and to assess the effect on ecosystem conversion of granting conflicting land-use designations, such as mining concessions, inside conservation areas. Using statistical matching and a GIS-based analysis of LULC, this research shows that for the period 2006–2011, designated conservation lands on the forest frontier of Madre de Dios significantly reduced ecosystem losses compared to non-conservation lands, but the effect was highly variable across conservation designations. Also, when present, conflicting land-use authorizations inside conservation areas, specifically overlapping mining and agricultural titles, eliminated the policy additionality of designating lands for conservation. This finding demonstrates that authorizing conflicting land-use rights inside conservation areas should be avoided to ensure intended land conservation outcomes. This case study also provides examples of how local forest conservation policies can be improved through detailed and frequent analyses of LULC and conservation policies, particularly in dynamic frontier landscapes where LULC and socio-economic conditions are rapidly changing.

1. Introduction

Globally, forest ecosystems provide a myriad of human benefits at multiple spatial scales, including the provision of ecosystem goods, such as timber and clean water, and the delivery of ecosystem services, such as carbon cycling (MEA, 2005). However, the widespread continued loss and degradation of forests around the world, particularly tropical rain forests, has led to calls for the adoption of additional forest conservation measures (e.g., Shearman et al., 2012; Laurance et al., 2012). Frequently, actions taken to advance forest conservation include implementing new conservation policies, including: new protected areas, international treaties, and payment for ecosystem service programs. Unfortunately, for most conservation policies, scientists and policy-makers still do not have a full understanding of their likely socio-environmental impacts and the optimum conditions for their application (Pullin and Knight, 2001; Parrish et al., 2003; Pattanayak et al., 2010; Miteva et al., 2012).

Over the last decade, in response to increasing awareness that conservation efforts could be improved with more empirical evaluation, a variety of studies evaluating the efficacy of conservation policies have been undertaken (e.g., Pattanayak et al., 2010; Miteva et al., 2012; Blackman, 2013). Frequently these studies have focused on assessing the effect of designating lands for conservation, including the global protected areas network (e.g., Joppa and Pfaff, 2010) and regional protected areas networks (e.g., Vuohelainen et al., 2012). Studies designed to assess the impact of designating lands for conservation suggest designated protected areas often have lower levels of land conversion than unprotected areas. Collectively, this body of research suggests that land

Abbreviations: LULC, land-use and land-cover change; ETM+, enhanced thematic mapper plus; TM, thematic mapper; RMS, root mean square error; GIS, geographic information system.

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designation can be an important factor influencing land conservation outcomes, but also that designation is only one factor among many that determine the efficacy of conservation policies (e.g., Scullion et al., 2011; Vuohelainen et al., 2012).

Since land designation is simply a title conferring a ''bundle of rights'' that legally determine who benefits from the land and how that land can be used (Robinson et al., 2011), targeted analyses of the systemic factors that determine the environmental outcomes of land designations are likely to yield insights that can inform comparable conservation activities. An important factor likely to influence the efficacy of designated conservation lands occurs when government agencies grant land-use rights to different parties that conflict, such as granting mining concessions inside authorized ecotourism concessions. Given that conflicting land-use authorizations are common in many parts of the world (e.g., Finer et al., 2008), it is surprising that the role of overlapping land designations on the efficacy of conservation outcomes has been poorly researched (but see Holland et al., 2013).

The great potential for unintended environmental outcomes resulting from authorizing overlapping and conflicting land-use rights within conservation areas suggests that conservation outcomes should be sensitive to the influence of conflicting land-use authorizations. In the Amazon region alone, many large-scale and conflicting land-use authorizations have already been implemented on designated conservation lands. Examples in Amazonia include: the Ecuadorian government's recent zoning of 65% of its Amazon territory, e.g., Ecuador's famous Yasuni National Park (Bass et al., 2010), for oil extraction; and the government of Peru granting oil leases on 72% of its Amazonian territory that includes designated conservation areas (Finer et al., 2008).

Because of the high potential for negative impacts from overlapping and conflicting land-use designations on the conservation and management of forests globally, this research examines this issue locally in Madre de Dios, Peru. In Madre de Dios, various affected land users have already identified overlapping land designations as problematic. For example, local Brazil nut gathers are facing logging threats from authorized forest concessionaires who have rights to harvest timber on approximately 1.3 million hectares of Brazil nut concessions, as well as from gold miners because mining concessions have been granted on top of 47,000 ha of Brazil nut concessions (Fraser, 2013).

To better understand how conservation designations and overlapping land conflicts influence conservation policies in Madre de Dios, this study used a mixed-methods approach to answer the following questions: (1) What is the efficacy, or policy additionality, of designated conservation lands on the rapidly expanding frontier of Madre de Dios for the period 2006–2011?, (2) What are the main factors influencing the efficacy of designated conservation areas?, and (3) How does granting conflicting land-use rights inside conservation areas, particularly mining concessions and agricultural titles, affect ecosystem conservation outcomes in areas designated for conservation?

2. Methods

2.1. Study area

Located in Peru's southeast Amazonian province of Madre de Dios, the 2,060,000 ha study area includes the majority of the province's contemporary LULC dynamics (Fig. 1). Madre de Dios is Peru's designated ''Capital of Biodiversity'' and part of the Tropical Andes Biodiversity Hotspot (Myers, 2001) (Federal Law 26311). Madre de Dios is also recognized worldwide as a conservation priority due to its relatively intact forests, exceptionally high levels of biodiversity, strategic location in connecting large wilderness parks in Peru, Bolivia, and Brazil, and projected resilience to climate change (Malhi et al., 2008; Killeen et al., 2008; Rosenthal et al., 2012). In addition to the high biological value of Madre de Dios and the western Amazon in general, the region is also home to a rich mosaic of cultural diversity that includes some of the last uncontacted indigenous groups living in voluntary isolation (Wessendorf, 2008; Shepard et al., 2010).

Prior to mid-1960, Madre de Dios had few inhabitants and little development. This changed after the construction of a road leading into the province. Since then, human population and land-cover conversion have increased substantially, and the region has experienced comparatively high levels of forest disturbance and deforestation within Peru (Oliveira et al., 2007). During the 1980s and 1990s, the loss of natural forests in Madre de Dios was primarily caused by government subsidized agricultural expansion (Alvarez and Naughton-Treves, 2003; Chavez and Perz, 2012). In the 2000s, gold mining became an important driver of regional LULC following the discovery of gold deposits and an increase in the international price of gold (Swenson et al., 2011; Asner et al., 2013). Since the discovery of gold, an estimated 30,000 artisanal miners have migrated to Madre de Dios (Webster, 2012). It is thought that ~95% of gold mining operations in the region are illegal because the miners either lack the proper permits to run their operations or because they are working outside authorized mining concessions (Keane, 2009a,b).

In addition to the expansion of gold mining, the recent completion of the Interoceanic Highway is also an important contributing factor to regional LULC due to its central role in facilitating local trade and resource extraction (Southworth et al., 2011). In 2011, approximately 68% of the study area was under one of six land designations that defined ecosystem conservation as a primary land-use objective (Table 1). At the same time, 94% of the study area was covered by natural ecosystems, including mature lowland rainforests, which comprised 69% of existing natural ecosystems, followed by montane forests, which were the second most abundant ecosystem (23.3%). The other existing natural ecosystems covered less than 3% of the total study area and included: palm swamps (2.9%), secondary lowland rainforests (2%), bamboo groves (1.6%), and riparian forests (0.9%).

In recent years, efforts by the government to regulate mining activities in Madre de Dios have led to intense social and political conflict. Much of this conflict is because the mining industry has created tens of thousands of local jobs, generates an estimated $369 million (USD) in annual revenue, and accounts for greater than 50% of all regional economic activity (Mosquera et al., 2009; GOREMAD, 2009). Due to the jobs and revenues generated, the local mining industry has become the region's dominant socio-political force, surpassing the economic importance of other local industries, including ecotourism, which still brings an estimated 50,000 tourists to the region each year (Kirkby et al., 2010). In addition to continued conflict over where gold mining should occur in the study area (e.g., in rivers and protected areas), a major socio-political issue facing the region is how several government agencies have authorized conflicting land-use rights to different parties for the same land. A recent example illustrating the local challenges presented by conflicting land-use authorizations is the ongoing dispute over forest management between Brazil nut harvesters who depend on specific large standing trees inside closed canopy forests and gold miners whose land-use activities generally require removing forest cover (Fraser, 2013).

2.2. Image classification and analysis

To analyze changes in land-cover over the study period, images acquired by NASA's Landsat sensors were classified for the years 2001 (ETM+ & TM), 2006 (TM), and 2011 (TM) (Path/row 2/69, 3/

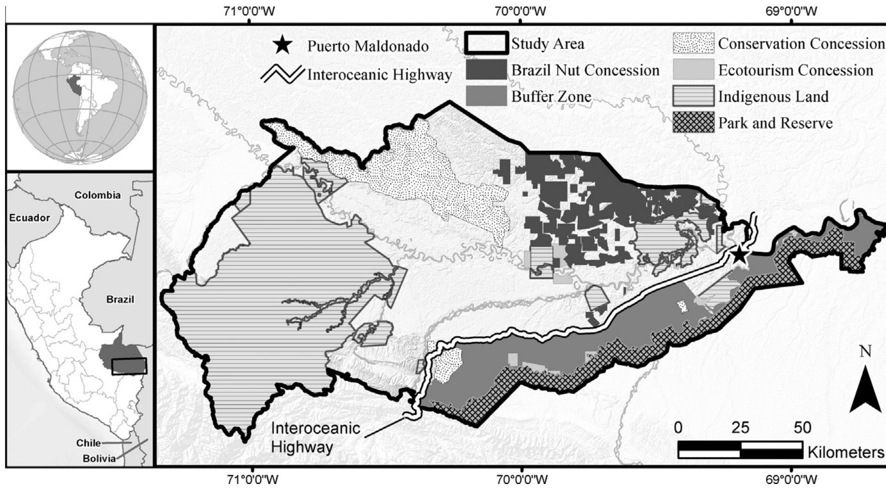

Fig. 1. Map of study area in Madre de Dios, Peru. The gray rectangle in the country map outlines the study area. The study area map shows the distribution of all designated conservation lands and their orientation relative to the Interoceanic Highway and the capital city of Puerto Maldonado.

Table 1
The table shows the total area and percent coverage of lands designated for conservation and non-conservation. See Vuohelainen et al. (2012) for a description of designated conservation lands and their authorizing legislation. Total land area in this table does not equal 100% due to rounding and missing coverage data for 2.5% of the study area (51,482 ha) and extensive overlapping between land-use designations. Also, because the majority of mining concessions overlap conservation and non-conservation lands, mining concessions were not evaluated as an independent land-use class outside of the land conflict analyses.

		Hectares	Study area (%)
Conservation Lands	Indigenous lands	679,784	33
	Reserve and park buffers	233,224	11
	Brazil nut concessions	184,365	9
	Conservation concessions	162,430	8
	Park & national reserves	128,589	6
	Ecotourism concessions	18,255	1
Non-Conservation Lands	Forest concessions	375,791	18
	Agriculture titles	187,939	9
	Reforestation concessions	64,369	3
	Mining concessions	155,596	7

68/, & 3/69). To ensure image comparability across sensors and acquisition dates, each scene was acquired during the same season (March–June). Each image was preprocessed using the following procedures: geo-rectification (<.5 RMS error), radiometric calibration, and atmospheric correction. Images were classified using a supervised classification approach in the spatial analysis software ENVI using the RuleGen decision tree classifier (RuleGen, 2004). RuleGen was trained iteratively based on a combination of (10–15) training samples, user and expert knowledge of the study area, and histogram enhanced Landsat images. Each classified land-cover map included "natural land-cover" (i.e., Primary Rain Forest, Secondary Rain Forest (<15 years old), Aguajale Swamps, Montane Forest, Riparian Forest, and Bamboo Forest) and "anthropogenic land-cover" (i.e., Agriculture, Infrastructure, and Mining), as well as Water (See Supplementary Material for classified maps).

Post-processing of the classified maps included a 3×3 majority filter to reduce noise, and extensive manual editing in ArcGIS version 10.1. Manual map editing was used to remove image classification errors and to delineate the natural bare-earth of riverbanks and streams from anthropogenic bare-earth resulting from artisanal mining (Swenson et al., 2011). Two local experts also improved the classified land-cover maps by identifying classification errors at several stages in the editing process. The final accuracy of each classified map was assessed using sixty reference points for each land-cover class, with the exception of the mining class in 2001, which only had 30 reference points, due to available imagery and the low number of clearly identifiable mining sites in 2001.

Reference points and training data for all land-cover classes were collected in the field using a hand-held GPS through a series of expeditions October–December 2011. The algorithms used to classify the land-cover classes Bamboo, Secondary Forests, Riparian Forests and Mining were developed by the authors using field validated training data collected throughout the study area. Reference points for these land-cover classes were user-generated based on histogram enhanced Landsat mosaics for each time period and field notes locating the land-cover in the field. The remaining forest cover classes, as well as the land-cover classes Infrastructure and Agriculture, were assessed entirely from GPS verification samples collected from the field. For all training data and verification samples taken with the GPS receiver, reference coordinates were only collected in areas that were unlikely to have changed land-cover classes before the beginning of the study. Overall accuracy for each map was: 87.7%, kappa 86.3 (2001), 86.5%, kappa 85.1 (2006), and 86.1%, kappa 84.6 (2011) (See Supplementary Materials). Land-cover change and land-use conflict were assessed using the spatial analysis software ENVI version 4.7 (Exelis Visual Information Solutions, 2009) and ArcGIS 10.1, respectively.

2.3. Statistical matching

To assess the additionality of designating lands for conservation and the influence of conflicting land authorizations on the efficacy of designated conservation areas, statistical matching was used (Ho et al., 2007; Ferraro, 2009). Matching is a robust statistical approach that can be used to assess the additionality of conservation designations because it provides an unbiased estimate of the treatment effect of land designation policies and allows for the user to control for the nonrandom distribution of designated conservation areas (Alix-Garcia et al., 2008; Joppa and Pfaff, 2010), which is particularly important given the tendency of protected areas to be located in more remote locations with lower risks of ecosystem loss (Pfaff et al., 2009; Joppa and Pfaff, 2009). Matching works in practice by using software to combine random samples of treatment and control variables into matched pairs to undertake an "apples-to-apples" comparison of their differential outcomes. This comparison is then used to estimate the treatment effect of the policy intervention (Joppa and Pfaff, 2011; Blackman, 2013).

To account for other factors that drive conservation outcomes besides the policy treatment, such as distance to major roads and population centers, pixel pairs are matched based on all observed covariates of ecosystem loss. After all possible pixel matches are made unmatched pixels are discarded. Policy additionality is estimated using a difference in means test of the matched samples, or the "average treatment effect on the treated" (ATT). In this study, ATT is used to measure the difference in outcomes of ecosystem loss for the 2006–2011 study period between: (1) lands designated for conservation versus non-conservation lands, and (2) lands designated for conservation versus lands designated for conservation overlapped by authorized land-use designations that generally "conflict" with ecosystem conservation objectives, i.e., mining concessions and agricultural titles.

For matching to provide an accurate measure of policy additionality, two underlying assumptions must be met: (1) all factors explaining ecosystem loss are the same for each set of matched pixel pairs, and (2) all observable covariates of ecosystem loss are included in the analysis (Blackman, 2013). To undertake a matching analysis in the study area, the covariates of ecosystem conversion were identified using a scatterplot matrix, which was used to test the collinearity of the selected spatially explicit variables (e.g., distance to roads and rivers). The final matching analysis included seven spatially explicit variables that were collinear with regional ecosystem conversion from 2006 to 2011 (Appendix A). All the covariates created and tested in the data creation process were independently correlated with regional ecosystem conversion and thus included in the final matching analyses.

The covariate variables used in this study were developed from a spatially explicit dataset created from a variety of sources, including public agencies in Peru and the United States (See Table 2). Most of the variables representing land-use designations were current in the year 2011 and thus may contain an incomplete record of land-use distribution in the year 2006. The effect of this time lag in available data is unknown, but likely to be minimal due to the low number of major changes in land-use designation 2006–2011. Also, due to the high level of land-use overlap in the study area, a caveat of this research is that some pixels used in the matching analyses were assigned several land-use classes. However, the potential influence on the matching analyses of dual land-use classifications for the same pixel is likely to be low due to the matching sampling design and the specific analyses undertaken. Each of the spatially explicit variables was created using the Zonal Statistic tool in ArcGIS 10.1, which allowed for features for each control variable to be extracted for each 30×30 m grid cell of the 2006 and 2011 land-cover maps. ArcGIS 10.1 was also used to standardize all data layer projections to WGS1984. To test the sensitivity of the matching results to the potential of unobserved confounders, a Rosenbaum Bounds test based on the Wilcoxon sign rank test p-value was used.

All matching procedures were performed in R using the 'matching' package (Sekhon, 2011), including the use of 'GenMatch,' which seeks optimal matched pairs using a genetic search algorithm (Diamond and Sekhon, 2005). To generate a robust sample of grid cells in the treatment and control groups, a random sample was drawn from 10% of the cells in the treatment areas and five times more cells in the control areas. The larger proportion of sample cells drawn from the control was designed to account for the highly skewed distribution of conservation lands

Table 2
The table shows the data sources used to estimate conservation effectiveness in Madre de Dios, Peru. The table lists the sources of each data type, the derived data value for the matching analysis, and the GIS variable name. Note Spanish acronyms for Peruvian data sources.

GIS variable	Derived value for matching	Data source
Distance to highways	Euclidean distance to secondary roads and the Interoceanic Highway	Ministry of Transportation and Housing (MTV)
Distance to rivers	Euclidean distance to rivers	Peru National Chart (scale 100,000). From Peru's National Geographic Institute (IGN). Produced 1960s through 1990s depending on topographic sheet
Elevation	Digital elevation value at 30 m intervals	ASTER GDEM. From The Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). 2011
Conservation status	Binary value of being conservation lands or non-conservation lands. See Table 1 for description of conservation and non-conservation lands. All land-use coverage data was current in 2011 unless noted	Regional Directorate of Agriculture (DRA). Regional Program of Forest Resource Management (PRMRFFS). National Protected Areas Service (SERNANP). Ministry of Culture
Conflict	Binary value based on the presence/absence of conflicting land-use rights overlapping at the same location. These "conflict lands" unless otherwise noted include designated conservation lands overlapped by mining concessions and/or agricultural titles. The conflict analysis was based on land-use data current in 2011 unless noted	Regional Directorate of Agriculture (DRA). Regional Program of Forest Resource. Management (PRMRFFS). National Protected Areas Service (SERNANP). Ministry of Culture
Soil type	Soil type is a measure of soil fertility based on the site-specific soil classification of semi-fertile riparian soils or nutrient poor upland soils	National Institute of Mining Geology and Metallurgy (INGEMMET). Production date unknown
Deforested 2001–2006	Binary value indicating the presence or absence of ecosystem conversion during the 2001–2006 study period	2001–2006–2011 NASA Landsat TM and ETM+ Classified Land-Cover Maps. Maps produced 2012
Distance to deforestation	The Euclidean distance to the nearest occurrence of ecosystem conversion during the 2001-2006 study period	2001-2006-2011 NASA Landsat TM and ETM+ Classified Land-Cover Maps. Maps produced 2012

in the study area, with most being located in more remote locations compared to non-conservation areas near the highway (Fig. 1). For each matching analysis performed, random samples of 100,000 cells were drawn from both the treatment and control groups. To account for the relatively small land area covered by ecotourism concessions in the study area (only 34,830 total cells) 200,000 cells were drawn to increase the number of potential matches available.

3. Results

3.1. Land-use and land-cover change 2001–2011

Landscape dynamics for the period 2001–2011 were complex and changed rapidly. Mining was the dominant driver of anthropogenic land-cover change, increasing during the period by 239% (9642 to 32,642 ha), while infrastructure, e.g., roads, buildings, and industrial areas, expanded by 44%, (1569–2264 ha). In contrast, agricultural lands declined by 10.8% (24,115–21,504 ha). The rate of ecosystem conversion, defined as the replacement of native vegetation by anthropogenic land-cover, was comparable between 2001 and 2006 (−0.5%) and 2006–2011 (−0.4%), but a major shift in the dominant driver of ecosystem conversion occurred with mining becoming more important than agriculture. From 2001 to 2006, agriculture was the dominant driver of LULC, explaining 53% of ecosystem conversion, whereas mining was the most important driver from 2006 to 2011, explaining 68% of ecosystem conversion.

A detailed analysis of ecosystem conversion for the period 2001–2011 shows that the total extent of natural ecosystems in the study area declined by 18,944 ha (−1.0%) and four of the five classified forest-cover types also declined in extent: riparian forests (−3.1%), lowland primary rainforests (−1.5%), palm swamps (−1.3%), and montane forests (−0.9%). Across the study area, a loss in the extent of cover for most forest ecosystems was contrasted by a 22% (7155 ha) increase in area of secondary forests. Overall, during the 10-year study period, substantial changes in the character and extent of local forest ecosystems occurred.

3.2. Influence of conservation designations on ecosystem conservation 2006–2011

A GIS analysis comparing ecosystem conversion levels between conservation areas and non-conservation areas found the total amount of ecosystem conversion and the overall rate of ecosystem conversion was higher inside conservation areas (−0.46%) compared to non-conservation areas (−0.09%) (Fig. 2). Also, total

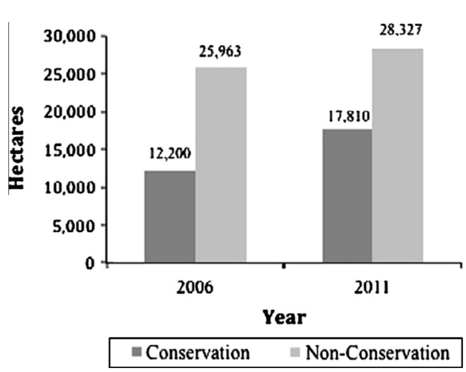

Fig. 2. The figure above shows total ecosystem conversion that occurred by area between designated conservation areas and non-conservation areas for the study period 2006–2011.

Table 3
The table shows total ecosystem conversion, percent ecosystem conversion by designation, and the estimated conservation effectiveness for all designated conservation areas for the period 2006–2011.

Land-use type	Ecosystem conversion		
	ha	Designation (%)	Estimated effect (%)
Conservation areas			
Indigenous lands	−4.314	−0.63	0.59
Buffer zones	−714	−0.30	2.19
Ecotourism concessions	−550	−3.01	2.86
Conservation concessions	−188	−0.12	2.61
Park & national reserves	54	0.04	3.14
Brazil nut concessions	102	0.05	2.76
Non-conservation areas			
Forest concessions	−3.133	−0.83	
Reforestation concessions	−1.944	−3.02	
Agricultural concessions	2.711	1.44	

rates of ecosystem conversion, overall amounts of ecosystem conversion, and the direct drivers of ecosystem conversion all varied by the type of conservation designation (Table 3 and Fig. 3). During the study period, an overall loss of ecosystem area occurred in 4 out of 6 types of designated conservation lands, including native lands, buffer zones, and ecotourism and conservation concessions (Table 3).

To assess the additionality of designating lands for conservation in the study area, matching was used to estimate the effect of the conservation designation policies in reducing the rate of ecosystem conversion (Ho et al., 2007; Ferraro, 2009). The results of the matching analysis show that the additionality of designating lands for conservation reduced ecosystem conversion inside designated conservation areas by 1.53% compared to non-conservation areas. Additionally, an evaluation of the relative conservation outcomes of each type of conservation designation shows the performance of each designation in preventing ecosystem conversion was highly variable (Table 3).

3.3. Influence of conflicting land authorizations on conservation additionality

Using GIS, it was estimated that in 2011, 64% of all designated conservation lands in the study area were overlapped by land designations granting conflicting land-use rights for resource extraction or land conversion, with nearly 49% of conservation lands overlapped by oil concessions, 13.3% by mining concessions, and 4.5% by agricultural titles (Table 4). Overlapping land designations authorizing conflicting resource extraction or ecosystem conversion were also found on 63% of non-conservation lands (549,242 ha). Moreover, even within conservation lands, an estimated 7% (88,435 ha) had two or more distinct conservation designations (e.g., Brazil nut concessions and national reserve).

The results of the matching analysis in estimating the impact of conflicting land authorizations on reducing ecosystem losses inside conservation lands, shows that conservation lands with no conflicting authorizations had an estimated 1.93% reduction in the rate of ecosystem conversion compared to a rate of 1.53% for all conservation lands, which included lands with conflicting land-use authorizations. Most importantly, the matching-conflict analysis shows that designated conservation lands with overlapping conflicting authorizations that authorize mining and/or agricultural activities on the same parcel had no significant effect on reducing the rate of ecosystem conversion. In other words, the matching-conflict analysis shows that from 2006 to 2011 there was no additionality of conservation designations in preventing ecosystem conversion in locations that were also overlapped by

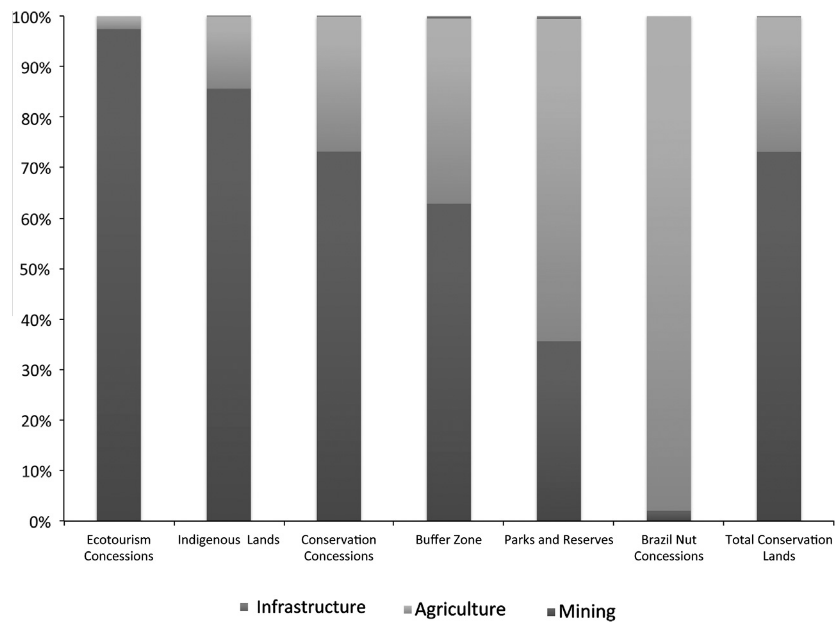

Fig. 3. The figure above shows the variation in the types of direct-drivers of ecosystem conversion between conservation designations for the study period 2006–2011.

Table 4
The table shows the percent coverage of conservation lands in 2011 with existing overlapping or "conflicting" land designations in total hectares and as a percentage of overlap by the total area of each designation type. * = The Total Land Conflict (ha) value included in the category Overall Conflict includes the total number of hectares of conservation lands that have one or more forms of conflicting land-use authorization, not the sum extent of all authorized land conflicts. Additionally, an estimated 105,901 ha of conservation lands have at least two overlapping and conflicting land-use authorizations. ** = Value represents total amount of conservation lands in the study area impacted by conflicting land designations.

Land designation	Overall conflict (%)	Mining conflict (%)	Agriculture conflict (%)	Oil conflict (%)
Indigenous lands	87	9	1	91
Ecotourism concessions	87	71	3	46
Reserve and park buffers	56	27	20	15
Parks and national reserves	35	5	1	30
Brazil nut concessions	28	18	1	13
Conservation concessions	28	6	1	21
Total land conflict (ha)	838,767*	187,186 (13.3%**)	64,276 (4.5%**)	693,206 (49%**)

land designations that authorize resource extraction or conversion, specifically mining and agricultural activities.

The GIS results of this study show that mining expansion was the dominant driver of ecosystem conversion during the 2006–2011 study period. During this period, 81% of all new mining activity that occurred inside conservation lands was inside authorized mining concessions. Similarly, mining expansion being concentrated inside authorized mining concessions was also more common within non-conservation designations. Overall, across the study area, the likelihood of new mining occurring inside mining concessions was 2.6 times greater than mining occurring outside mining concessions. While most of the new mining expansion inside conservation areas did occur in authorized mining concessions, 19% of new mining occurred outside mining concession areas. Conservation areas with the highest levels of new mining outside authorized mining concession were indigenous lands (24.4%) and the park and reserve buffer zones (15.9%).

4. Discussion

A major goal of this research is to identify policy recommendations, or "best practices," to improve forest conservation policies in frontier environments. Likewise, an important goal is to demonstrate the value of combining analyses of policy efficacy with studies of LULC to improve the design of forest conservation policies. To this end, the explicit objectives of this research are to evaluate the influence of conflicting land-use authorizations on ecosystem conversion and extend the work of Vuohelainen et al. (2012) to assess the additionality of designating lands for conservation in Madre de Dios, Peru, particularly in light of the rapid expansion of new gold mining areas.

4.1. The additionality of conservation designations and the underlying drivers

A primary finding of this study is that despite widespread and increasing ecosystem conversion across the study area for the period 2006–2011, the additionality provided by designating lands for conservation was significantly greater than non-conservation lands. However, the rate and total area of ecosystem losses inside designated conservation lands was still higher than inside non-conservation lands. More specifically, this study's update on the 2005–2008 matching results reported by Vuohelainen et al. (2012) concurs that designated conservation lands still had an overall positive effect in preventing ecosystem conversion relative to non-conservation lands. Yet, conservation lands still experienced widespread ecosystem losses and had greater overall losses than non-conservation lands. These contrasting results are likely the result of mix of factors, including the distribution and concentration of new mining expansion and the widespread variability in local land conversion risk.

Examining the explicit reasons that explain the relative performance of the conservation designations is informative for local policy-making and it also highlights a suite of broader policy insights for assessing and implementing ecosystem conservation policies in frontier landscapes. For example, within the park and reserve areas, specifically Peru's Tambopata National Reserve and Bahuaja-Sonene National Park, an important finding of this analysis is that despite the rapid increase in gold mining near designated park and reserve areas, the park and reserve still provided the best overall conservation outcomes. The strong performance of the national park and reserve is likely related to several factors, including the increasing presence of park guards, park managers' recent engagement in resolving land disputes, and the relatively consistent presence of scientists and eco-tourists (personal communications).

Like parks and reserves, Brazil nut concessions also experienced an overall increase in ecosystem area. This finding of additional land-cover protection being conferred by Brazil nut concessions is particularly interesting given the results of a recent study finding that the amount of wood being extracted from Brazil nut concessions in Madre de Dios was comparable and in some cases even higher than the amount being extracted from logging concessions (Cossío-Solano et al., 2011). Unfortunately, this pattern of ecosystem change was not detected in this study due to the unique challenges of identifying the occurrence of selective tropical forest logging using traditional remote sensing approaches. Principally, the diffuse nature of selective logging and the fast closure of tropical canopy gaps following selective logging (Asner et al., 2006; Montellano and Armijo, 2011) can make it challenging to detect this form of land-use change.

The two poorest performers among designated conservation areas were the buffer zones of the national reserve and park and indigenous lands. The reasons why the park and reserve buffer zones experienced relatively high levels of loss and low policy additionality is also likely due to high occurrence of mining authorizations inside the buffer areas, the relatively high levels of unauthorized mining outside mining concessions, and the presence of extensive and newly discovered gold deposits. Surprisingly, indigenous lands were estimated to be the least effective conservation designation. The low efficacy of indigenous lands in Madre de Dios preventing ecosystem conversion differs sharply with findings in the nearby Brazilian Amazon. In Brazil, indigenous lands have been shown to perform as well or better than other land-use designations under high deforestation pressure (Nepstad et al., 2006; Nolte et al., 2013; Schwartzman et al., 2013). Several explanations can be posed for the low conservation performance of indigenous lands in Madre de Dios, including unauthorized mining by non-indigenous people inside indigenous territories and the active participation in mining activities of ten local native communities (MINAM, 2011).

Overall, despite the widespread conversion of native ecosystems inside designated conservation lands, this study shows that designating lands for conservation can result in intended conservation outcomes even in frontier landscapes with high conversion pressure and the widespread occurrence of conflicting land-use authorizations. This study also supports other research reporting that the efficacy of land designations leading to ecosystem conservation is tightly linked to many other site-specific socio-environmental factors (e.g., Joppa et al., 2008; Nolte et al., 2013). Collectively, these findings suggest that policy-makers and resource managers working in frontier landscapes must develop ways to adapt to the dynamic and diffuse nature of land-use pressures. If the local context surrounding dynamic land-use pressures is not consistently considered in conservation policy design and resource management, many frontier conservation goals may not be maintained over the long-term.

4.2. Impacts of conflicting land authorizations on ecosystem conservation

In addition to highlighting the complexity of competing factors influencing the efficacy of conservation designations, this research also shows the significant influence and extensive coverage area of conflicting land-use authorizations in the study area. Of principal importance, this research shows that the additionality of designated conservation lands is effectively negated when conflicting land-use designations are overlapped in the same location, specifically agriculture and mining areas. This finding is largely the result of new gold mining expansion inside conservation areas, which is concentrated primarily inside authorized mining concessions. Also, the greater overall effectiveness of all conservation lands without conflicting authorizations compared to all conservation lands including conflicting authorizations shows that conservation lands without conflicting authorizations are generally more effective in ecosystem conservation than conservation lands with conflicting authorizations. This analysis thus supports the conclusion that efforts towards improving conservation outcomes inside designated conservation areas in the study area would benefit from mitigating and/or reducing overlapping land-use conflicts.

This study's GIS and LULC analyses also demonstrate the linkage between new gold mining primarily occurring inside authorized mining concessions inside conservation and non-conservation lands. For the period 2001–2011, the areal extent of gold mining across the study area increased by 239%. Of the new mining that occurred inside designated conservation areas, 81% was located inside authorized mining concessions. Also, mining was responsible for greater than 70% of the ecosystem conversion that occurred from 2006 to 2013 in 4 out of 6 conservation designations, including the buffer zones, ecotourism and conservation concessions, and indigenous lands. These same 4 of 6 designations were also the only conservation designations to experience net ecosystem losses during the study period. In other words, while mining concessions overlap only 14% of total conservation lands, the presence of mining concessions inside conservation areas was significantly related to the overall effectiveness of conservation lands in preventing ecosystem conversion.

Most likely, the link between authorizing mining concessions in conservation areas and new gold mining is the result of a combination of factors specific to each location, such as the location and extent of gold discovered, the ease of industrial access, and the existence of existing mining concessionaires, among other socio-environmental factors. An insight that flows from this analysis of the influence of mining concessions on conservation policy efficacy is that while illegal mining outside of authorized mining concessions explains some of the increase in ecosystem loss in conservation areas in Madre de Dios, the majority is explained by the presence of authorized gold mining concessions. In turn, this study shows that authorizing gold mining concessions inside conservation areas is likely to result in reduced protected areas effectiveness and increased ecosystem losses.

Given the extent of conflicting land-use authorizations in Peru and other Latin American countries (e.g., Finer et al., 2008), it is surprising that so few studies have been published on the impacts of overlapping land-use designations on conservation policy efficacy (Holland et al., 2013). Holland et al. 2013, which explored and identified overlapping land tenure regimes and also controlled for the nonrandom distribution of protected areas, found that overlaps in parks and indigenous lands actually provided greater conservation benefits compared to "pure" park areas without overlapping indigenous lands. Of course, this positive report of Holland et al. (2013) contrasts sharply with the negative environmental outcomes highlighted in this study. These differences point to the need to further explore how conflicting (or co-benefiting) land-use designations can influence conservation outcomes. This conclusion is further bolstered given ample evidence demonstrating the importance of social conflict and land tenure claims in driving conservation outcomes, including degazettement of parks (Mascia and Pailler, 2011), increased land clearing to demonstrate ownership (Aldrich et al., 2012), and reduced deforestation due to increased tenure security (Robinson et al., 2011).

4.3. Policy insights to advance forest conservation in frontier environments

In addition to the support this research provides in identifying the negative effect of conflicting land-use authorizations on local conservation areas, the results of this study also highlight several policy recommendations for managing and assessing forest conservation policies in frontier environments.

First, to ensure forest conservation policies are tightly and continuously matched to the dynamic forces of local LULC, frequent analyses of LULC dynamics are critical. In this case study the importance of a high frequency of land cover analysis is illustrated by the rapid shift in LULC dynamics over the ten year study period, particularly the shift from a dominance of agricultural expansion to a decline in agricultural areas and the rapid expansion of gold mining. Unraveling the reasons for this shift is difficult with this study design, but the reasons likely rest on the relative economic returns of gold mining compared to agriculture. For example, a typical miner in Madre de Dios makes approximately \$10–230 USD per day (Keane, 2009a,b; PBS, 2011; Sapienaza, 2011) whereas a typical manual farm laborer earns \$15–18 USD per day (personal communications). Given the high wage disparity between gold miners and low skilled labors outside the mining industry, it is likely that the higher wages and profits earned by gold mining was a major factor driving the shift in LULC dynamics from agriculture to mining. This conclusion is further supported by government data showing field prices paid to farmers in Madre de Dios actually went up for 18 out of 19 crops grown in the region from 2006 to 2011 (MINAG, 2013), but still remained low compared to economic returns from gold mining.

A second policy recommendation highlighted by this case study is that detailed analyses of the impacts of LULC on local ecosystems are critical to identify conservation priorities and design effective conservation and development policies. A familiar example supporting this finding is how during the study period 2001–2011, the area of several ecosystem types decreased at a higher rate than the overall rate of ecosystem conversion of the study region (−1%). For example, higher decreases in areas were found for the particularly species rich primary rainforest (−1.5%) and riparian forests (−3.1%). These more detailed results show not only what ecosystems are being lost at the highest rates, but also the speed and widespread impact of ongoing gold mining activities on priority ecosystems.

5. Conclusions

LULC dynamics and conservation additionality in the study area are the direct result of a complex interaction of local, regional, and international factors. This case study shows that like many active forest frontiers around the world, the efficacy of the conservation area system in Madre de Dios would benefit from rigorous and frequent analyses to monitor LULC and conservation policy outcomes. This case study also shows that conservation areas in the study area faced intense land-conversion pressure and experienced high rates of ecosystem loss, even compared to non-conservation lands, but overall regional conservation areas policies had a positive effect on ecosystem conservation. Likewise, this case study shows that to ensure the policy additionality of designating lands for conservation, authorizing conflicting land-use authorizations should be avoided when possible.

These findings also indicate that much greater attention should be given to the study and management of conflicting land-use authorizations in Madre de Dios and beyond, especially given the great negative impact conflicting land-use authorizations may have on future social conflict and global conservation outcomes. Likewise, given the potentially large negative effects of conflicting land-use authorizations on people, communities, and conservation outcomes within the Amazon region for the foreseeable future, robust strategies for mitigating and resolving this form of land-use conflict are needed. Such strategies should include efforts to develop refined approaches for micro-zoning, habitat corridor planning, and targeted site selection of conservation and development activities. Also as highlighted by Fraser (2013), the creation of an integrated government land registry system in Madre de Dios could help resolve existing land conflicts and avoid future ones. Lastly, this study again makes clear that designing effective forest conservation strategies requires the intelligent combination of mutually supporting conservation and development policies (Porras et al., 2011; Scullion et al., 2011).

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Appendix A

The table above shows pre- and post-matching results from ‘Match’.

Designation type	Control and treatment matches		Covariates	Before treatment	Before control	SD	T stat	After treatment	After control	SD	T stat
Indigenous lands			Conflict	1.071	1.0269	17.172	3.20E−14	1.0278	1.0262	0.94442	0.086943
	Original number of observations (obs.)	100,000	Deforested 01-06	0	0.014234	Inf.	<2.22e−16	0.013695	0.016563	−2.4673	2.83E−05
	Original number of treated obs.	74,831	Distance to Deforestation	1297.5	10316	−433.2	<2.22e−16	10159	10055	0.81052	0.14412
	Matched number of obs.	63,992	Distance_to_Highway	6797.4	15659	−147.12	<2.22e−16	15534	15766	−1.7196	0.0018833
	Number of unmatched obs.	36,008	Distance_to_River	1919	3171	56.522	<2.22e−16	3142.6	3327.6	−6.2301	<2.22e−16
			Elevation	274.09	316.6	−61.059	<2.22e−16	315.95	309.78	4.7612	<2.22e−16
			Soil_type	0.43644	0.40586	6.164	0.0064235	0.40538	0.39857	1.3868	0.013384
Park and reserve buffer zone			Conflict	1.0911	1.0502	14.233	<1.8111e−11	1.051	1.061	−4.5346	<7.8604e−14
	Original number of obs.	100,000	Deforested 01-06	0	0.018338	Inf.	<2.22e−16	0.017854	0.029074	−8.4728	<2.22e−16
	Original number of treated obs.	88,729	Distance to Deforestation	1361.5	5997.3	−220	<2.22e−16	5887.4	6156	−3.0904	<7.5842e−08
	Matched number of obs.	59,537	Distance_to_Highway	6463.8	11750	−88.232	<2.22e−16	11615	11744	−1.1308	0.050925
	Number of unmatched obs.	40,463	Distance_to_River	2015.6	3410.8	−61.398	<2.22e−16	3374.6	3652.8	−8.8726	<2.22e−16
			Elevation	276.82	279.1	−3.1451	0.13688	278.83	284.35	−8.3719	<2.22e−16
			Soil_type	0.37599	0.42638	−10.402	<9.7459e−07	0.42726	0.40185	5.1372	<2.22e−16
Ecotourism concessions	Original number of obs.	200,000	Conflict	1.0013	1.0039	−7.3503	0.00057915	1.0035	1	5.904	<1.9124e−09
	Original number of treated obs.	99,470	Deforested 01−06	0	0.018527	Inf.	<2.22e−16	0.017273	0.059539	−32.439	<2.22e−16
	Matched number of obs.	11,470	Distance to Deforestation	1280.7	6373.6	−254.43	<2.22e−16	6185.8	4816.6	15.362	<2.22e−16
	Number of unmatched obs.	188,530	Distance_to_Highway	6613.7	11943	−85.74	<2.22e−16	11686	6755.7	43.346	<2.22e−16
			Distance_to_River	1905.3	3497.3	−71.396	<2.22e−16	3449.8	2959	15.473	<2.22e−16
			Elevation	273.46	282.92	−13.765	<4.601e−11	282.27	288.57	−9.5695	<2.216e−13
			Soil_type	0.41373	0.43677	−4.6769	0.024905	0.43868	0.72373	−57.441	<2.22e−16
Conservation concessions	Original number of obs.	100,000	Conflict	1.0046	1.006	−2.1329	0.32607	1.0053	1.0011	5.8105	<2.22e−16
	Original number	92,413	Deforested 01−06	0	0.017523	Inf.	<2.22e−16	0.017189	0.033925	−12.876	<2.22e−16

(*continued on next page*)

Appendix A (*continued*)

Designation type	Control and treatment matches		Covariates	Before treatment	Before control	SD	T stat	After treatment	After control	SD	T stat
	of treated obs.										
	Matched number of obs.	28,681	Distance to Deforestation	1267.5	7298	−289.94	<2.22e−16	7265.9	7104.6	1.5664	0.064462
	Number of unmatched obs.	71,319	Distance_to_Highway	6615.7	13302	−109.58	<2.22e−16	13261	13546	−2.2337	0.010374
			Distance_to_River	1992.9	3427.1	−61.476	<2.22e−16	3379	3710.2	−10.532	<2.22e−16
			Elevation	273.06	286.16	−18.939	<2.22e−16	285.92	285.87	0.080525	0.92258
			Soil_type	0.41457	0.40677	1.5824	0.46469	0.40996	0.42328	−2.708	0.0011831
Park & national reserve	Original number of obs.	100,000	Conflict	1.0017	1.0041	−5.5339	0.0099015	1.004	1.0006	5.381	<2.22e−16
	Original number of treated obs.	93,889	Deforested 01−06	0	0.01748	Inf.	<2.22e−16	0.01743	0.0036768	10.509	<2.22e−16
	Matched number of obs.	42,972	Distance to Deforestation	1363.1	6271.9	−226.81	<2.22e−16	6125.3	7401.3	−14.442	<2.22e−16
	Number of unmatched obs.	57,028	Distance_to_Highway	6362.8	12261	−97.971	<2.22e−16	12080	12273	−1.6893	0.011009
			Distance_to_River	1998.7	3423.9	−59.928	<2.22e−16	3376.7	3491	−3.6709	<1.4058e−07
			Elevation	271.97	279.02	−10.545	<6.318e−07	278.57	278.15	0.63694	<2.22e−16
			Soil_type	0.4102	0.4462	−7.3164	0.00054352	0.44655	0.42253	4.8308	<1.3363e−12
Brazil nut concessions	Original number of obs.	100,000	Conflict	1.0014	1.0188	−46.854	<2.22e−16	1.019	1.0044	10.703	<2.22e−16
	Original number of treated obs.	90,813	Deforested 01-06	0	0.017927	Inf.	<2.22e−16	0.017491	0.023218	−4.3683	<7.9775e−16
	Matched number of obs.	51,340	Distance to Deforestation	1322.7	6334.2	−235.38	<2.22e−16	6262.4	4830.4	16.305	<2.22e−16
	Number of unmatched obs.	48,660	Distance_to_Highway	6662.2	13632	−112.12	<2.22e−16	13580	16979	−26.064	<2.22e−16
			Distance_to_River	2021.5	3814.8	−77.464	<2.22e−16	3759	4054	−8.3004	<2.22e−16
			Elevation	272.8	282.29	−13.561	<5.0507e−10	282.02	281.63	0.62232	0.30475
			Soil_type	0.40065	0.39515	1.1215	0.60626	0.3972	0.33007	13.717	<2.22e−16
Conservation vs. non-conservation	Original number of obs.	100,000	Conflict	1.1652	1.0744	24.433	<2.22e−16	1.0752	1.0831	−3.0038	<8.2752e−07
	Original number of treated obs.	58,070	Deforested 01-06	0	0.012946	Inf.	<2.22e−16	0.013001	0.0098751	2.7595	<8.3261e−07
	Matched number of obs.	56,303	Distance to Deforestation	1212.7	9791.8	−436.6	<2.22e−16	9592.3	9226	3.0187	<3.607e−07
	Number of unmatched obs.	43,697	Distance_to_Highway	6560.9	17240	−179.83	<2.22e−16	17006	16645	2.5746	<1.5717e−05
			Distance_to_River	2059.2	3306.4	−55.364	<2.22e−16	3290	3160.4	4.0563	<4.4791e−12
			Elevation	272.3	305.86	−50.382	<2.22e−16	305.13	301.14	3.3698	<5.57312e−09
			Soil_type	0.43028	0.36741	12.695	<2.9339e−07	0.36611	0.35674	0.077423	0.8965

Appendix A (*continued*)

Designation type	Control and treatment matches		Covariates	Before treatment	Before control	SD	T stat	After treatment	After control	SD	T stat
Conservation vs. conservation in conflict	Original number of obs.	100,000	Deforested 01-06	0	0.0047295	Inf.	<2.22e−16	0.0046783	0.0033574	1.9357	0.045491
	Original number of treated obs.	18,243	Distance to Deforestation	1289.5	14406	−633.55	<2.22e−16	14394	14813	−2.935	0.0060098
	Matched number of obs.	18,213	Distance_to_Highway	7651.6	24536	−304.02	<2.22e−16	24517	24378	0.99668	0.34789
	Number of unmatched obs.	81,787	Distance_to_River	1937.7	3006.2	−52.511	<2.22e−16	3029.6	2840.6	5.9432	<6.3932e−09
			Elevation	269.03	336.07	−122.46	<2.22e−16	333.98	332.23	1.1211	0.27848
			Soil_type	0.5634	0.27595	57.923	<2.22e−16	0.27316	0.28086	−1.7293	0.10214

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2014.01.036.

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