

**Gold Mining and Land Cover Change in Madre de
Dios, Peru: A Remote Sensing Study Using Landsat-5
Thematic Mapper Data**

A Thesis

**Submitted in partial fulfillment of the
Requirements for the Award of Honors in
Environmental Science**

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**Clark University
Worcester, Massachusetts**

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ABSTRACT

Gold Mining and Land Cover Change in Madre de Dios, Peru: A Remote Sensing Study

Using Landsat-5 Thematic Mapper Data

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Peru has reputedly the largest non discovered gold resources on earth. In a country with a 30% poverty rate, artisanal and small-scale mining (ASM) offers a source of employment and a strategy to fight poverty among the low income sectors of the population. ASM is found in four geographic regions: Central South (Ica, Ayacucho and Arequipa), Puno, La Libertad and Madre de Dios. Few government regulations and low cost of mining operations are driving land cover changes on these locations, but to unknown extent and magnitude. The following study applies Landsat-5 Thematic Mapper (TM) data to create land cover maps and detect land cover changes between 1986 and 2011 resulting from artisanal and small-scale gold mining for a ~10316 km² region in the Department of Madre de Dios, southeastern Peru. TM images from 1986, 1996, 2006 and 2011 were used to map five categories: dense forest, water, cleared land and sediment, mine tailings and grassland. Overall map accuracy ranged between 81-84%. Throughout the 25-years period, forest cover decreased by 915.98 km² (7.09%), cleared land and sediment increased by 105.06 km² (0.81%), grassland increased by 348.35 km² (2.70%), as did mine tailings, which increased by 396.15 km² (3.07%). Dense forest areas contributed to an increase in grassland (44.35%), mine tailings (38%) and cleared land and sediment (17.65%). Land cover changes in Madre de Dios are caused by ASM activities in concessions *with title* (53.4%), in concessions *with title in progress* (12.6%), and in areas outside the boundaries of mining concessions and mining claims (34%).

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Introduction

Peru is the sixth-largest producer of gold worldwide with a 7.68% market share (Vasquez and Balistreri, 2010). Unfortunately, 20% of Peru's bullion originates from illegal Artisanal and Small-scale mining (ASM) (Gardner, 2012). Illegal mining activities, together with informal and legal ASM operations result in forest loss, water and land pollution, river damage, and abandoned pits and shafts (Hentschel et al., 2002). Today the extent and current state of ASM in Peru is unknown (Mosquera, 2009). However, ASM deprives the Peruvian government of an estimated US\$305 million in taxes each year (Gardner, 2012). Despite the fact that ASM is so widespread, it has received little political or analytical attention (Alvarez et al., 2011). The government has continued to attract foreign investment in larger scale projects by reducing subsidies and tariffs, treating ASM as a low priority concern (Low, 2012). The absence of efforts to enforce either environmental or social standards allows ASM activities to continue unabated (Swenson et al., 2011).

The Department of Madre de Dios generates 70% of Peru's artisanal and small scale gold production (Ministry of Energy and Mines in Brooks et al., 2007). ASM in Madre de Dios is responsible for more than 32,000 ha of forest loss (Fraser, 2009). In 2011, over 1546 mining claims overlapped with natural protected areas, their buffer zone, and in indigenous land holdings as reported by the Peruvian Ministry of the Environment (Alvarez, 2011). The Peruvian government hopes to prevent ASM from encroaching into protected areas including Los Amigos Conservation Concession, Amarakaeri Communal Reserve, Tambopata National Reserve and Manu National Park, UNESCO's World Heritage Site (Gardner, 2012).

Mapping and monitoring illegal mining in Madre de Dios is a challenging task. There is no clear estimate of the number of illegal miners, nor the percent that have applied for mining

permits (Swenson et al., 2011). However, it is critical to estimate the ASM impact on the surrounding environment. Unregulated management of hazardous substances, such as mercury, is a recurrent threat (Ashe, 2012). Mercury poisoning among women and children living in mining villages is higher than among miners, as miners work in the only “non-contaminated” environment, the mine (Hentschel et al., 2002). An estimated of 45-50 tons of mercury are used annually in Madre de Dios (Gardner, 2011). Large quantities of this metal are lost to the atmosphere, waters and soils resulting from burning of gold-mercury amalgam, discharging metallic mercury into rivers during the amalgamation process, and mercury leaching from mine tailings (See Malm, 1998; Yard et al., 2012). ASM operations lack the required environmental impact assessment, and no effort is made to restore or rehabilitate terrain that has been deforested and transformed (Dourojeanni et al., 2009).

Mining activities in Peru increased substantially after the Spanish Conquest in 1532 (Mosquera, 2009). Throughout the Colonial period the country experienced an influx of European fortune hunters who decreased the indigenous population due to harsh working conditions in the mines, as part of the “mita” system (Dammert and Molinelli, 2007). In 1877, the dawn of foreign investment during the Republic triggered the passage of a Peruvian Law which allowed foreigners to own mines, re-opening exploration and mining activities in the country (Dammert and Molinelli, 2007). During the 1980s, the expansion of ASM operations became a source of employment and a social alternative for improving the livelihoods of Peruvian people affected by the economic crisis, declining agricultural fortunes, and the displacement of people during the civil war (Mosquera, 2009). In the late 1980s, rising gold prices and lack of employment opportunities in other industries produced the growth of ASM operations (Swenson et al., 2011).

In 2002 the Toledo administration passed the Law 27651 that established an initial framework to regulate, formalize and promote ASM (Low, 2012). Only few ASM operations obtained permits due to the high cost of the formalization process (Low, 2012). In 2006, during the Garcia administration, the formalization, regulation and monitoring of ASM operations were transferred to regional authorities but failed to grant regional governments the necessary training to ease the process (Arguedas et al., 2011). In 2011, the Humala administration used repressive measures to regulate illegal mining of both artisanal and medium scales, and did not provided support to those seeking formalization (Low, 2012). Currently, there are no consistent policies on ASM despite its rapid growth over the past thirty years (Low, 2012). In many areas of the country, ASM operations represent the only viable form of profitable economic activity for those living under the poverty line (MMSD, 2002). In fact, a third of a million Peruvians make their living from gold mining, while illegal practices and deforestation damage the environment and inflict health risks on the local population (Sapienza, 2011).

A small but significant set of research papers have addressed the issue of monitoring mining impacts using remotely sensed data. Latifovic et al. (2005) used Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapper-Plus (ETM+) imagery to track trends in vegetation productivity to estimate the rate of abrupt versus transitional land cover changes in the Athabasca Oil Sands Region in Canada. Surface disturbance resulting from mining activity was identified by mapping and comparing land cover distributions, post-classification change detection methods, and by calculating the Normalized Difference Vegetation Index (NDVI) (Latifovic et al., 2005). Results showed an 8.64% decrease in natural vegetation over nine years, whereas NDVI trend analysis indicated that greenness near mining areas decreased by 15% (Latifovic et al., 2005).

Akiwumi and Butler (2008) used multitemporal Landsat TM images and field data associated with rutile mining locations to study the effects of mining on drainage systems in Sierra Leone between 1967 and 1995. Five land cover categories including natural drainage, dredge-ponds and reservoirs, cleared land and sediment, tailings, and vegetation were identified using maximum likelihood classification. Spectral similarities between cloud cover and tailings, and dredge-ponds and natural water bodies limited the quantification of individual categories (Akiwumi and Butler, 2008). Rutile mining operations between 1967 and 1995 impacted 66 km² (4.8%) of the 1367 km² mine concession in southwestern Sierra Leone. The area covered by dredge ponds increased from 6.93 km² to 36.94 km² (Akiwumi and Butler, 2008).

Swenson et al. (2011) used Landsat-5 TM imagery (2003 - 2009) to map the conversion of forest on the two fastest growing mining areas in the Department of Madre de Dios (i.e., Guacamayo, between the Inambari River and the Inter-Oceanic Highway, and an area between the Colorado and Puquiri rivers). Results indicated that from 2003 to 2009 ~6600 ha of primary tropical forest and wetlands were converted to mine-related ponds and tailings (Swenson et al., 2011). The forest conversion rate increased six-fold from 2003-2006 (292 ha/yr) to 2006-2009 (1915 ha/yr), and it was linked to an annual increase in gold prices of ~18%/yr (Swenson et al., 2011).

There are several studies addressing the impacts of mining on forest cover; however, remote sensing studies that estimate the amount of forest cover change in ASM locations in Peru are limited (see Mosquera, 2009, Swenson et al. 2011, Alvarez et al., 2011). The difficulties in addressing the environmental impact of ASM development in Madre de Dios are accentuated by the fact that there are misconceptions about the characteristics of ASM operations (Hentschel et

al., 2002). “Artisanal”, “informal”, and “illegal” are terms used interchangeably to describe any mining activity not carried out by internationally recognized commercial entities (Low, 2012).

The Peru Support Group (2012) provided a classification based on the extent of mined area and the characteristics of mining operations (Table 1). Artisanal mining refers to operations up to a 1000 ha which excavates less than 25 metric tons of material per day, as established by Law 27651 (2002). This classification does not refer to the extraction processes or the extent to which this activity complies with local legislation. The Law 27651 recognizes “Small-scale” operations, up to 2000 ha and excavation of 350 tons of material per day (2002). Informal mining operations occur on any scale; however, informal miners can become legally registered and fully licensed (Law 27651, 2002). Illegal miners have no interest in becoming officially registered; they operate without paying taxes or holding permits and/or formal title to their claims (Fraser, 2009). Illegal miners focus on short term gains and have the worst environmental and labor practices (Low, 2012). Illegal operations in Madre de Dios have caused the most environmental damage (Sapienza, 2011).

This study considers three types of ASM: operations inside mining concessions that hold a title or permit is defined as formal (legal). Informal mining occurs in areas that have applied for a mining permit, but it is still in progress. Lastly, illegal mining activities can be found outside the boundaries of mining concessions and mining claims. The research objectives are: 1) to amend Swenson’s work by using multitemporal Landsat data for 1986, 1996, 2006 and 2011 to map gold mining impacts on forest cover over a 25-years period; 2) and to estimate the proportion of total land cover change caused by each type of artisanal and small-scale gold mining in the Department of Madre de Dios, along the Colorado, Inambari and Tambopata subwatersheds.

Study Area

The Department of Madre de Dios is located in the most southeastern region of Peru bordering Brazil and Bolivia (Figure 1). Madre de Dios has a total area of $\sim 85,000 \text{ km}^2$; approximately 6% of its area is occupied by legal mining concessions – *with title* ($\sim 5045.95 \text{ km}^2$), whereas 3.5% correspond to mining claims waiting for a permit – *title in progress* ($\sim 3025.35 \text{ km}^2$). The dominant vegetation type is lowland tropical rainforest with a mosaic of well-drained forest floor (*terra firme*), swamp forests (*aguajal*), and forests adapted to annual flooding (*tahuampa*) (Vuohelainen et al., 2012). The area has an altitudinal range of $\sim 1500 \text{ m}$ in the foothills of the Andean eastern Cordillera to 300 m in the Amazon lowland forest (Belcon, 2012). The climate is largely humid tropical and the region experiences seasonal climate with a dry period from April to September and an average annual precipitation between $1,500$ and $3,000 \text{ mm}$ (SENAMHI, 2011). The mean monthly minimum temperature is 16.8°C , occurring in July and the mean monthly maximum temperature is 32°C , occurring in October (Goulding, 2010). The region is divided into three provinces: Manu, Tambopata and Tahuamanu, with Puerto Maldonado as the capital city. Madre de Dios is one of the lesser populated Departments of the country with $109,555$ inhabitants, which represents 0.4% of the national population (INEI, 2011).

The area under study is $\sim 10316 \text{ km}^2$. Legal mining concessions occupy 34.75% ($\sim 3584.65 \text{ km}^2$), whereas mining claims cover 26.5% ($\sim 2733 \text{ km}^2$) of the study area. Alluvial gold placer deposits are found along the riverbeds of the Madre de Dios River and its tributaries: Tambopata, Inambari and Colorado. Illegal and informal mining zones are located several miles away from the road in order to limit the access by government officials (Ashe, 2012). However ASM zones are rapidly expanding in the rainforest along the Interoceanic Highway, the main

transportation route in this region (Swenson et al., 2011). ASM sites in Madre de Dios are described as cleared land from primary rainforest loss, with the presence of small swamps which contain sufficient level of gold and surrounding space to support miners and their rigs (Figure 2) (Ashe, 2012). Most of the mining zones transition into sprawling shanty towns (Ashe, 2012).

Data and Methods

The USGS Global Visualization Viewer (GloVis) provided 30 m Landsat-5 TM (Path 3, row 69) satellite imagery for the dates July 12, 1986; July 23, 1996; August 04, 2006 and September 3, 2011. The image dates cover the period of most intense mining in the study area and September images correspond to the mid-dry season with minimum climatic variations (SENAMHI, 2011). The steps of image processing, classification, and comparative assessment required in this analysis are presented in figure 3. Atmospheric correction was performed using the Cos(t) model (Chavez, 1996) which was proven to be a reasonable technique to remove atmospheric scattering effects in Landsat data in the Amazon basin (Lu et al., 2002). Ancillary data include mining concession and mining claim polygons (1986 – 2011), a 92.8 m digital elevation model (DEM), a geomorphologic and physiographic map of Madre de Dios, and stream layers obtained from the Peruvian Ministry of the Environment (MINAM) Geoserver. The Global Land Cover Change Facility provided a 60 m Amazon Forest Change Map from 1990 that includes forest, water, degraded forest, and non-forest / grassland classes. Geometric registration was performed on the Amazon Forest Change Map, using nearest neighbor interpolation obtaining a RMSE of 6.57.

A false color composite of Landsat bands 4 (Red), 3 (Green), and 2 (Blue), together with ancillary land cover maps, Earth imagery from 2010 (Google Earth 2012) and on-screen

visualization were used to classify the biophysical parameters and mine features in the study area. Five land cover categories were identified: dense forest (primary and secondary forest), water (natural drainage including rivers and reservoirs; and dredge ponds resulting from mining activities), cleared land and sediment (mining and deforested areas), mine tailings (located along the edges of dredge ponds and riverbeds), and grassland (small scale farming, pastures and periodically mowed meadows). Masks were created to remove clouds and avoid the mixing of spectral signatures.

Land cover classification uses polygonal areas of interest (AOI) or training sites for each given year to characterize land cover types across the study area (Vaclavik and Rogan, 2009). Ten training sites with a minimum of 50 pixels per site were selected for each land cover category (see Table 2). To assess the separability of selected training sites, spectral signatures of individual land cover classes were created using feature space images and scatterplots (Vaclavik and Rogan, 2009).

Stratified random sampling was performed on the 1990 Amazon Forest Change Map and on the false color images for 1986, 1996, 2006 and 2011 to select ground reference points in order to create the general reference data for the classification and map accuracy assessment processes (Jensen, 2004). A sample size of 100 random points were selected, 20 per land cover category.

The Land Change Modeler (LCM) (Eastman, 2006) was applied for land change detection analysis for times t_1 and t_2 . LCM evaluates gains and losses in land cover classes, land cover persistence and specific transition between each category. Using the classified maps from 1986, 1996, 2006 and 2011 as input parameters, LCM identified the location and magnitude of

major land cover changes and persistence among land cover classes and between different time periods.

Results

Each Landsat image was classified into five thematic classes: dense forest, water, cleared land and sediment, mine tailings and grassland (Figure 4). The reference data was compared to the classified maps to determine overall map accuracy, average commission and omission error (Table 3). Per-class omission and commission errors were also calculated. In the 1986 map, the overall accuracy was 84%; there was a 17% average commission error and 15% average omission error. The omission error for cleared land and sediment (33%) and mine tailings (30%) indicated a high probability that both land cover types were present in the study area. The same occurred with dense forest, its omission error value was 14%. The grassland category also had a high probability of being present in the study area as indicated by its low omission error (25%). However grassland's high commission error (47%) implied that the areas mapped as grassland may not be covered by this category. It is possible that some other categories were misclassified as grassland areas and vice versa as there were not many areas that will fall under this land cover class before the beginning of mining operations.

The overall map accuracy for 1996 was 81%, average commission error was 23% and average omission error was 18%. Omission error for dense forest (13%), grassland (18%), and mine tailings (16%) indicated high occurrence of these categories in the study area. In fact, a 17% commission error for mine tailings implied that 83% of the areas classified as this category are really so. The 2006 map had an overall accuracy of 83%; average commission error was 19% while average omission error was 17%. Omission error for dense forest and mine tailings is 17%

and 20% respectively. Commission error was low for grassland (30%), cleared land and sediment (20%), and mine tailings (21%); thus the areas mapped as having those categories were correctly covered by them. Finally the overall accuracy for the 2011 map was 82%; average commission error was 18%, while average omission error was 20%. Omission error for dense forest and cleared land and sediment classes was 18% and 16% respectively. Similarly, commission error was low for mine tailings (20%) and cleared land and sediment (19%) classes.

LCM identified the nature of land cover changes and determined the magnitude and direction of individual changes. The results of the cross-tabulation comparison of the land cover maps indicated significant changes for all land cover categories between 1986 and 2011 (Figure 5). Attention was paid to the dense forest, cleared land and sediment, and mine tailings because they are the focus of the study. Results from LCM showed that from 1986 to 1996 the total area of grassland decreased by 197.60 km^2 (1.53% of the total study area), while the area of mine tailings increased by 160.04 km^2 (1.24% of the total study area). Cleared land and sediment decreased by 20.34 km^2 (0.16% of the total study area), whereas dense forest increased by 38.05 km^2 (0.29% of the total study area). By the year 2006, the proportion of land covered by grassland increased by 295.56 km^2 (2.29% of the total study area). Mine tailings decreased by 61.10 km^2 (0.47% of the total study area), as did cleared land and sediment, which decreased by 1.01 km^2 (0.01% of the total study area). Similarly, dense forest experienced a loss of 276.25 km^2 (2.14% of the total study area).

In the year 2011, the proportion of area covered by grassland increased by 250.39 km^2 (1.94% of the total study area). As people continued migrating to gold mining locations, shanty towns sprang up to provide services to the people who work there. The area covered by mine tailings increased by 297.21 km^2 (2.30% of the total study area). Cleared land and sediment

increased by 126.41 km² (0.98% of the total study area). The proportion of areas covered by dense forest decreased by 677.77 km² (5.25% of the total study area). Over the 25 year period (1986 - 2011), dense forest experienced the greatest loss compared to the other four categories. The total area of dense forest decreased by 915.98 km² (7.1% of the total study area), while the area of cleared land and sediment increased by 105.06 km² (0.81% of the total study area), as did grassland areas, which increased by 348.35 km² (2.7% of the total study area). The proportion of areas covered with mine tailings increased by 396.15 km² (3.07% of the total study area).

To identify the transitions between land cover classes, we focused on those that experienced an increase in their total area during the study period: grassland, mine tailings and cleared land and sediment. We calculated the contributions of other categories to their net change, i.e., which classes in t_1 map were identified as grassland, mine tailings and cleared land and sediment in t_2 map and what proportion of the total change for a land cover class and proportion of the study area they explain. The majority of the increase in mine tailings from 1986 to 1996 is explained by the transition from the dense forest class (61%), which represents about 0.76% of the entire study area. Others contributors to the increase in mine tailing areas are the categories of grassland (20%) and cleared land and sediment (20%), which represents a total of 0.40% of the entire study area (Figure 6.a). Similarly, the areas covered by dense forest explain the majority of the total increase in grassland (94.32%) from 1996 to 2006 (Figure 6). This transition occurred on approximately 2.16% of the total study area. By the year 2011, dense forest contributed to an increase in grassland (103%), mine tailings (90.43%) and cleared land and sediments areas (91.83%) (Figure 7). This transition represents approximately 5% of the total study area. Throughout the 25 years period, dense forest contributed to an increase in

grassland (44.35%), mine tailings (38%) and cleared land and sediment (17.65%). The transition of dense forest to other land cover classes occurred in 6.63% of the entire study area (Figure 7).

In order to visually identify areas of change from 1986 to 2011, a cross-classification map was produced to evaluate the total land cover change for the 25-years period (Figure 8). The landscape of the study area and the characteristics of ASM activities in the region allows for a rapid recognition of mining locations, especially in the following areas: the Colorado-Puquire micro-watershed, known as Delta 1; the Huepetuhe-Caychive micro-watershed; and the Guacamayo micro-watershed.

Cumulative land cover change resulting from artisanal and small-scale gold mining operations occurred in $\sim 1430.43 \text{ km}^2$ ($\sim 14\%$ of the total study area). The proportion of land cover change in Madre de Dios caused by activities in mining concessions *with title* is 53.4%, whereas land cover change resulting from mining in locations *with a title in progress* is 12.6%. Lastly, mining activities outside the boundaries of mining concessions or claims represents 34% of the total land cover change, which is assumed to come from illegal mining operations (Figure 9). The transition between specific land cover categories from 1986 to 2011 in km^2 is shown in Table 4.

Discussion and Conclusion

Remote sensing techniques and satellite imagery analysis proved to be useful in showing the dynamic nature of mining and the resultant changes in land cover and transition from dense forest to mine tailings, cleared land and sediment, and grassland areas. Our objective was to identify the locations and types of the major land cover changes from 1986 to 2011 in Madre de Dios. The post-classification assessment of remotely sensed data is as accurate as the

classification results used in the analysis (Vaclavik and Rogan, 2009). Maximum likelihood classification was successful in identifying dense forest, water, cleared land and sediment, mine tailings and grassland. Mine tailings and cleared land and sediments were the most challenging categories to classify because of their spectral similarity and the lack of field data and reference points. Obtaining such data was not possible for the purpose of this study. Stratified random sampling was performed on the 1990 Amazon Forest Change Map to generate ground control points, independent from the training sites and use them for accuracy assessment purposes.

The overall accuracy of the four classified land cover maps is within the standard range of 80-85% (Rogan et al., 2003). Omission and commission errors for individual land cover categories were also estimated. The 1986 map had the highest overall accuracy compared to the other three years. Categories of water and dense forest had omission and commission error values lower than 20%, due to the high separability of their spectral signatures. Similarly the categories of mine tailings and cleared land and sediment depicted low omission errors. In 1996 and 2006 commission and omission error values were $\leq 30\%$ for all the land cover classes. Similarly, the 2011 map, mine tailings and cleared land and sediment categories had omission and commission error values less than 20%.

Despite the accuracy of the maximum likelihood method, each classified map has approximately 13 m of inherent positional error associated with the study owing to the relationship between the smallest object being mapped, in this case tree crown (approximately 17 m) in areas of intermediate dry season length (1 – 3 months) (Barbier et al., 2010), and the spatial resolution of the Landsat-5 imagery (30 m).

The quantitative analysis using Land Change Modeler provided an estimate on the total area of forest loss from 1986 to 2011. Though no empirical evidence of direct causality between

land cover changes and Peru's socio-economy crisis in the early 1980s is provided by this study, the results revealed that artisanal and small scale mining activities represent a total decrease of 915.98 km² (7.1% of the total study area) of forest cover. This figure does not reflect other indicators of environmental disruption such as ecosystem and water quality changes. The loss of dense vegetation accounts for an increase of cleared land and sediment (0.81% of the total study area), and mine tailings (3.07% of the total study area) during the 25 year period. Dense forest areas along the Colorado-Puquire micro-watershed (Delta 1), the Huepetuhe-Caychive micro-watershed, and the Guacamayo micro-watershed transitioned to cleared land and sediment and mine tailings areas. These observations are indicator of rapid sprawling of artisanal and small-scale mining operations in the area, most of which are known to be illegal.

Even though most ASM activities in Madre de Dios follow streams and rivers, patches of mining operations away from water resources appeared between 2006 and 2011. The results of this study showed the impact of artisanal and small-scale gold mining activities in the region, as well as the proportion of mining related land cover change for each of the three types of ASM operations. The study also revealed that ASM operations are encroaching inside the buffer zones of natural protected areas. These areas correspond to the Colorado-Puquire micro-watershed (Delta 1) and the Guacamayo micro-watershed which have access to water for processing (i.e. small dredge ponds).

The rapid growth of mining activities in Madre de Dios is the result of lack of policies to enforce and regulate environmental or social standards. Deforestation resulting from uncontrolled mining practices constitutes a major threat for humans and the environment. The magnitude of the problem and the need for accurate information such as the quantity and size of

illegal mining settlements, together with the current status of mining concessions require the Peruvian Government to reinforce, revise and develop effective environmental policies.

This study monitored and quantified land cover changes in the southern region of the Department of Madre de Dios, Peru resulting from ASM operations. Four land cover maps were produced, indicating the relative abundance of five land cover types. Techniques of geographical analysis, classification of multispectral satellite data and comparison of produced land cover maps, together with knowledge of the study area, field data, etc. represent an effective alternative to develop and improve environmental monitoring, management and policy strategies in developing countries. Future work will include a more comprehensive, empirical classification method, such as the use of decision tree classifier instead of deterministic methods in order to directly incorporate other landscape variables such as topography, hydrology, higher resolution land cover maps, which ought to improve the accuracy of the classification. In addition, higher resolution imagery and extensive field validations would be useful to map department-wide mining activity and discriminate the spectral signatures of mining sites from migrating rivers or mine tailings.

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Tables

Table 1: Categories of mining in Peru. ASM is used to refer to all categories of mining outlined in red below. “Non-formal” operations are those shaded in dark grey. Large-scale illegal and informal mining are excluded from this group as there are no examples of this in Peru. (Source: Peru Support Group)

Size	Type		
	Illegal	Informal	Formal
Artisanal (<25 tons/day)	x	x	x
Small-scale (<350 t/d)	x	x	x
Medium-scale (<5,000 t/d)	x	x	x
Large-scale (>5,000 t/d)			x

Table 2: Number of pixels for each of selected training fields

Feature	Number of pixels in training fields			
	1986	1996	2006	2011
Dense Forest	392093	176956	704916	288097
Water	1535	1338	1745	2438
Cleared land and sediments	687	1944	4371	3893
Mine tailings	256	385	737	836
Grassland	477	538	1910	14429

Table 3: Accuracy assessment results

Accuracy elements	1986	1996	2006	2011
Overall accuracy	84%	81%	83%	82%
Average commission error	17%	23%	19%	18%
Average omission error	15%	18%	17%	20%

Table 4: Transition between specific land cover categories from 1986 to 2011 in km².

Land cover category	1986 -1996	1996 -2006	2006-2011	1986 - 2011	Percent of total change (1986-2011)
Water to Dense forest	6.14	24.04	12.55	9.01	0.61
Cleared land and sediment to Dense forest	73.23	64.39	5.36	52.58	3.58
Mine tailings to Dense forest	18.77	115.07	25.56	11.64	0.79
Grassland to Dense forest	179.51	14.87	129.64	81.17	5.53
Dense forest to Water	30.72	49.06	46.40	69.13	4.71
Cleared land and sediment to Water	25.22	34.62	22.37	35.63	2.43
Mine tailings to Water	1.59	12.29	2.48	2.73	0.19
Grassland to Water	3.79	1.04	3.43	9.95	0.68
Dense forest to Cleared land and sediment	67.34	65.24	121.24	203.82	13.88
Water to Cleared land and sediment	29.62	27.31	45.73	21.16	1.44
Mine tailings to Cleared land and sediment	6.26	29.38	21.59	8.29	0.56
Grassland to Cleared land and sediment	20.73	4.22	10.94	32.25	2.20
Dense forest to Mine tailings	116.36	85.94	294.15	337.27	22.96
Water to Mine tailings	5.35	1.84	9.88	11.70	0.80
Cleared land and sediment to Mine tailings	39.41	16.45	36.66	38.98	2.65
Grassland to Mine tailings	26.66	8.05	31.91	35.82	2.44
Dense forest to Grassland	25.18	294.38	389.09	460.15	31.33
Water to Grassland	0.36	1.03	2.76	9.16	0.62
Cleared land and sediment to Grassland	6.43	11.70	8.70	33.27	2.27
Mine tailings to Grassland	1.12	16.65	25.77	4.96	0.34

Figures

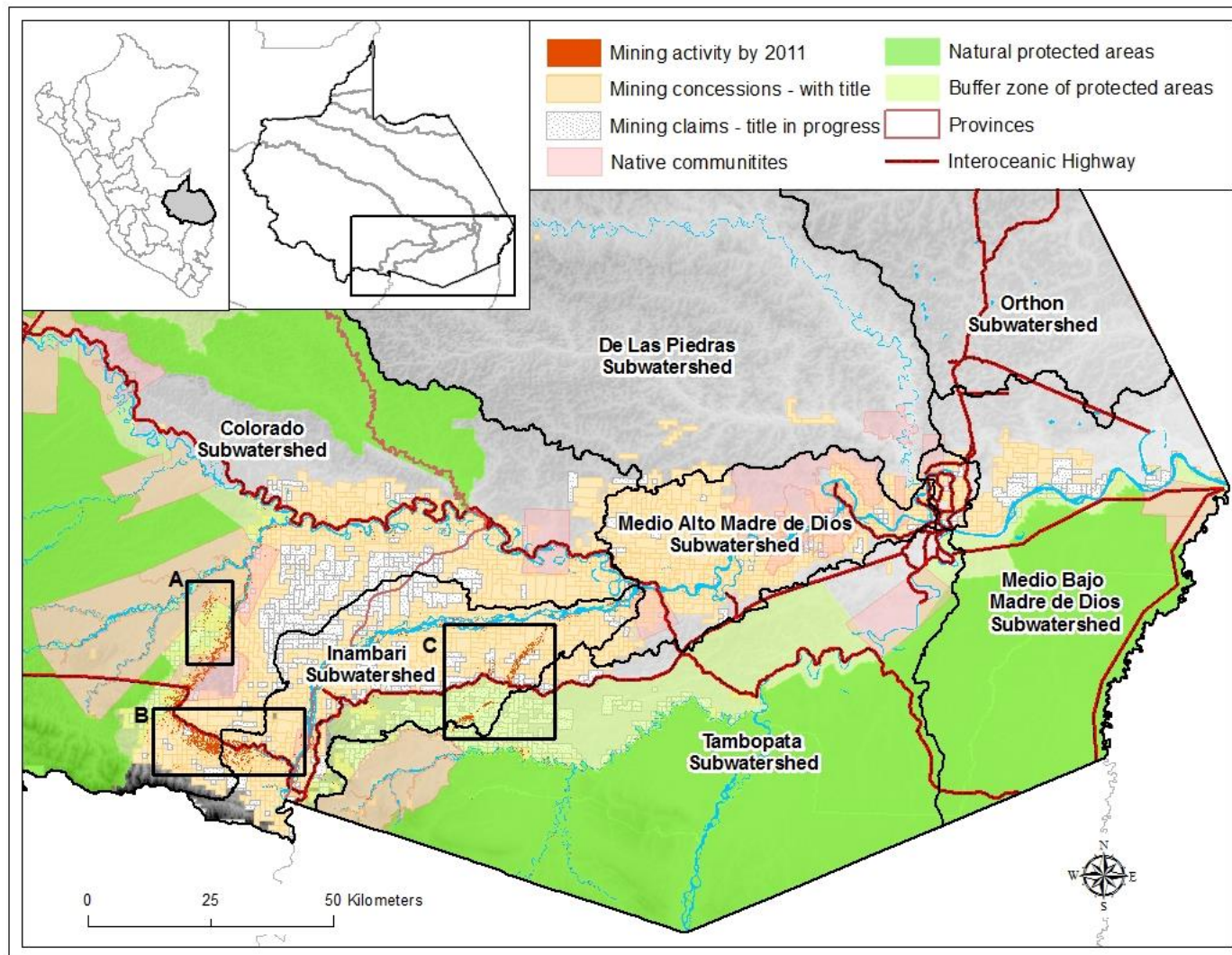


Figure 1: Study Area Map: Department of Madre de Dios, Peru. Mining areas denoted by “A”, for Colorado-Puquire micro-watershed, known as Delta 1; “B” Huepetuhe-Caychive micro-watershed; and “C” for Guacamayo micro-watershed.

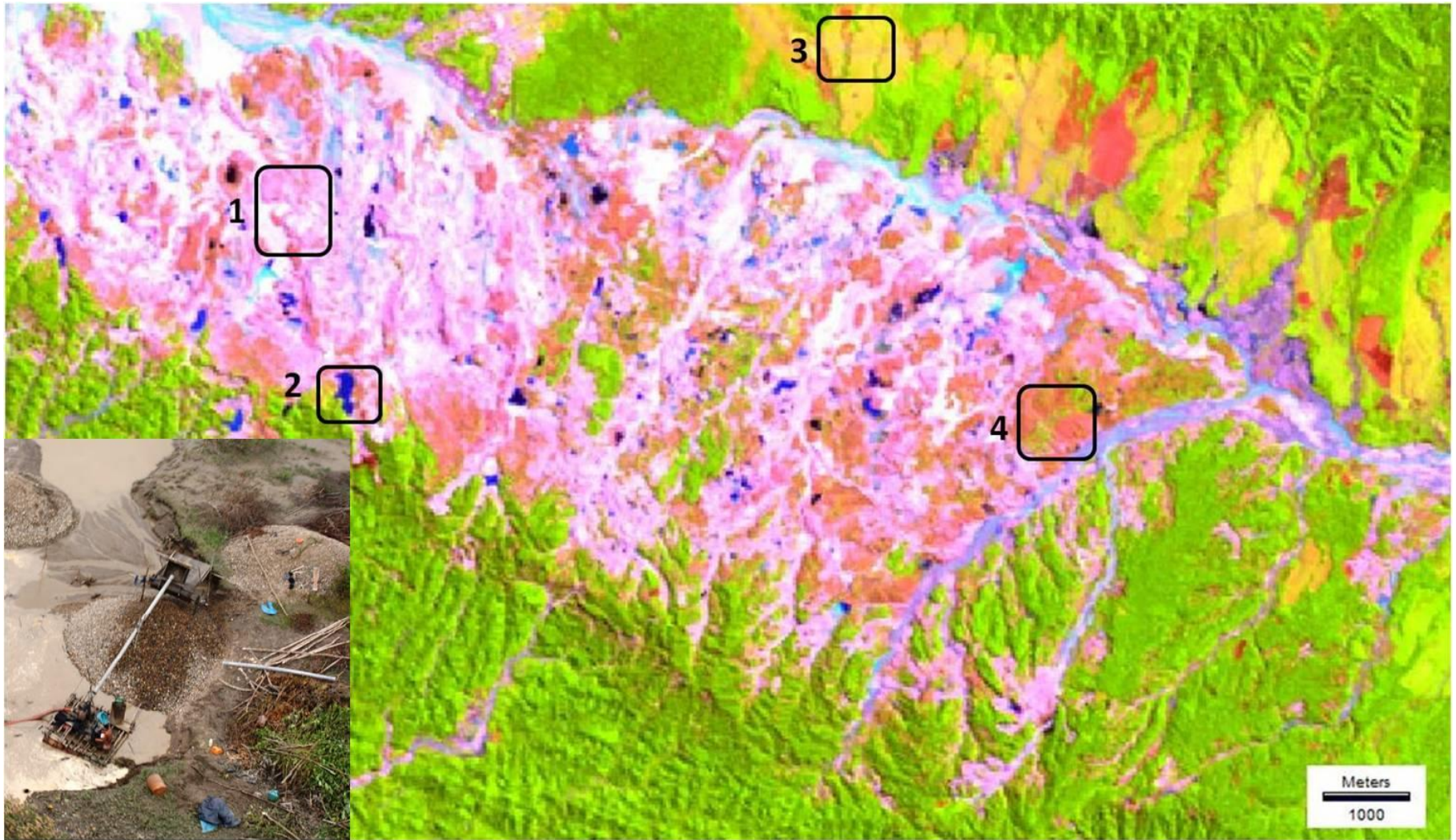


Figure 2: Traditional ASM operations in Madre de Dios (Photo credit: MINAM, 2009). “True Color” composite of a mining area using Landsat bands 3 (Blue), 4 (Green) and 5 (Red). Boxes represent (1) cleared land and sediment, (2) swamps (dredge-ponds, water), (3) grassland (small scale farming, pastures and periodically mowed meadows), and (4) mine tailings.

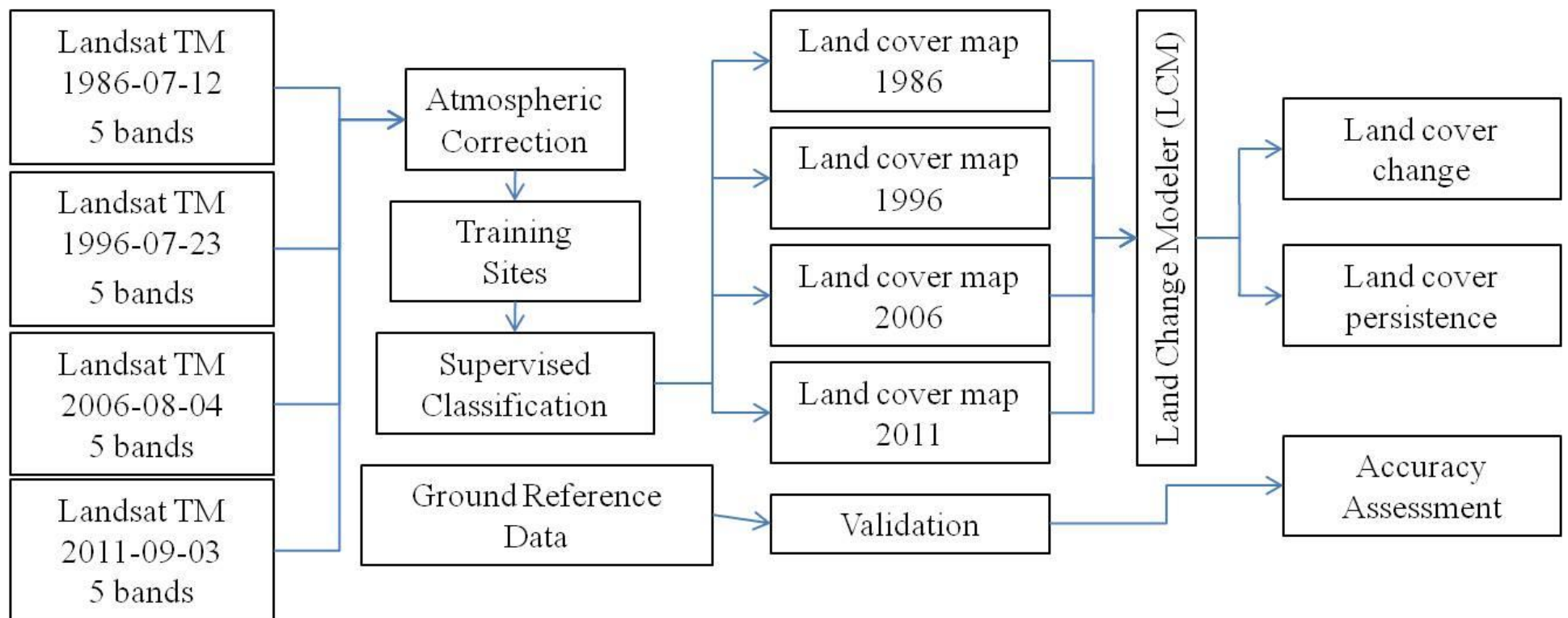


Figure 3: Flow chart of input data, methodology and outputs used in the analysis.

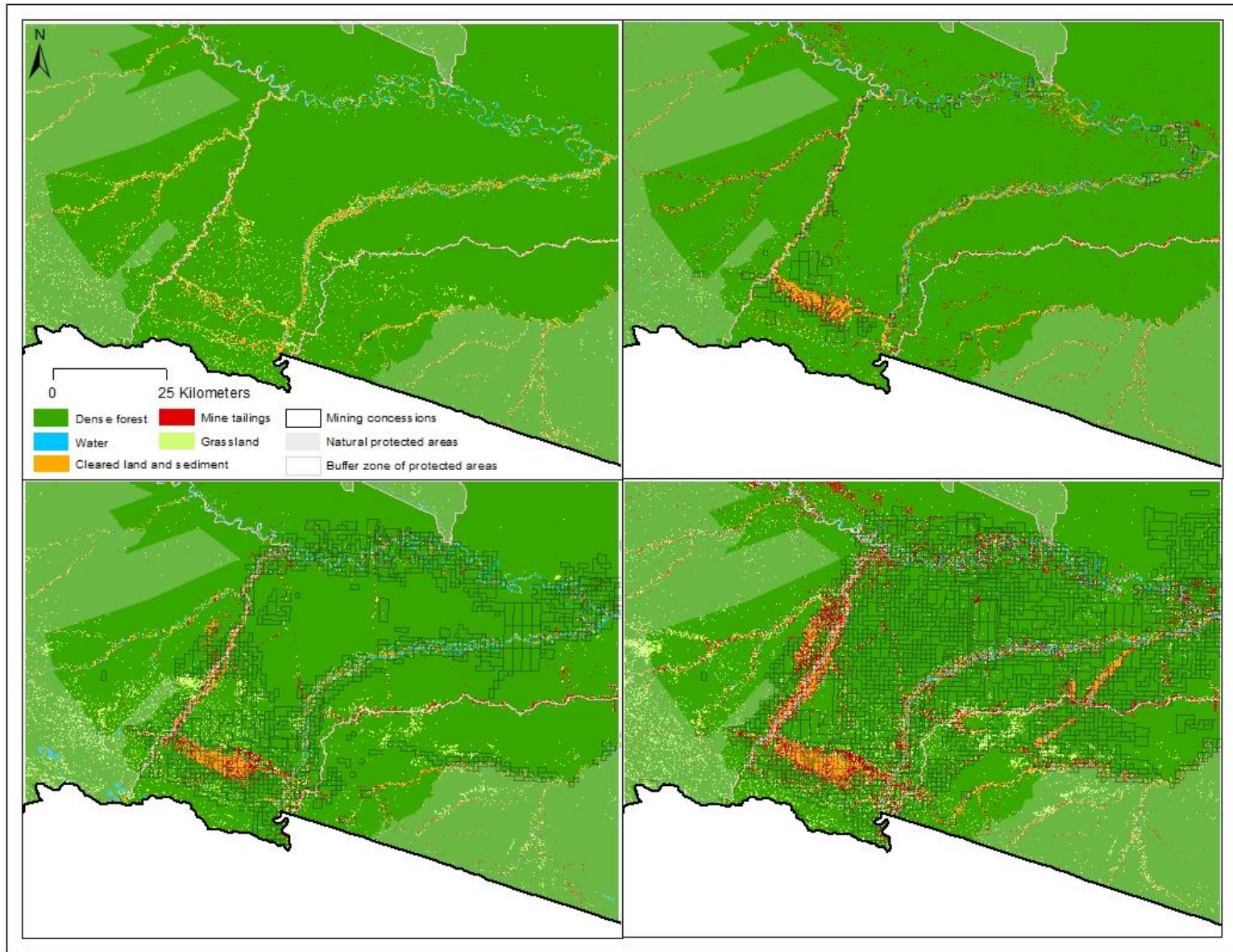


Figure 4: Maximum likelihood classification maps for 1986 (top left), 1996 (top right), 2006 (bottom left) and 2011 (bottom right).

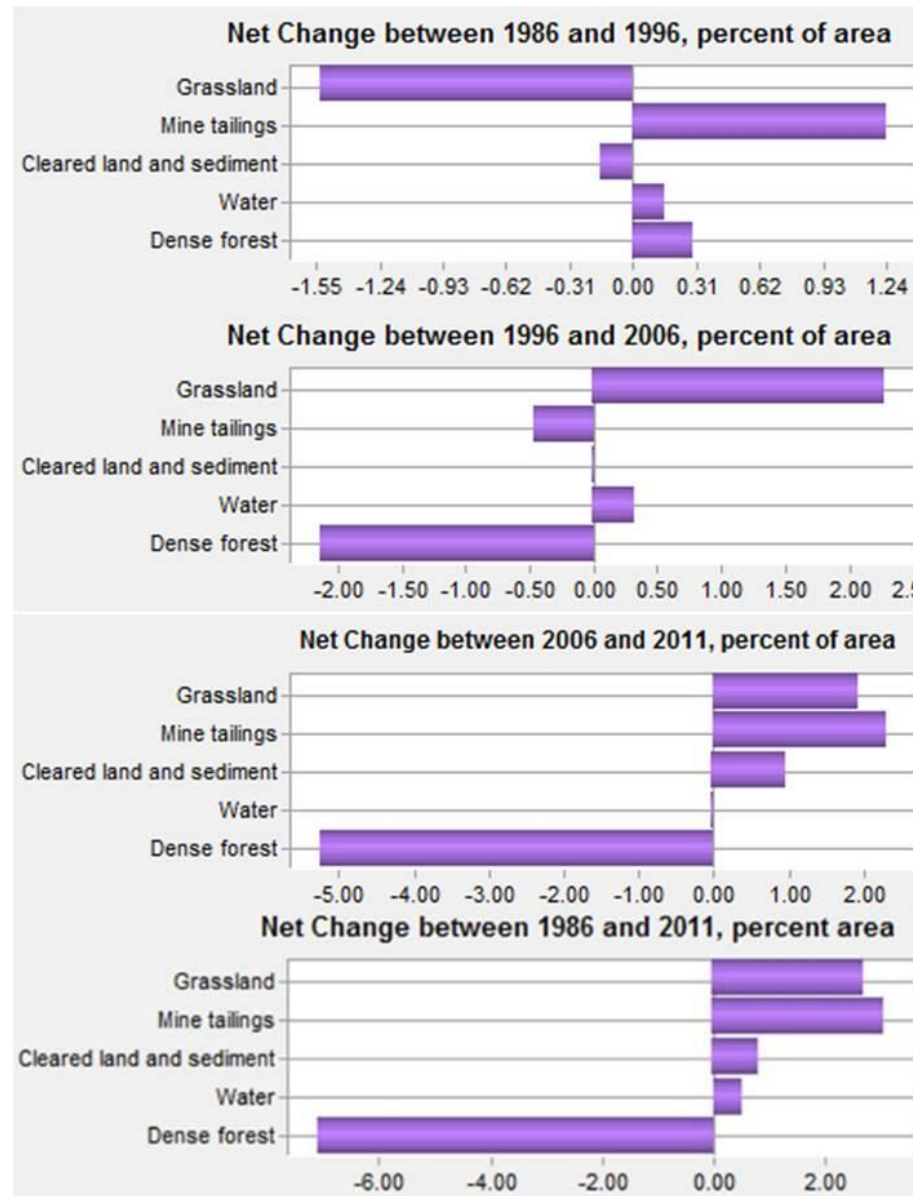


Figure 5: Net change in land cover categories between 1986 and 2011 in percent of study area.

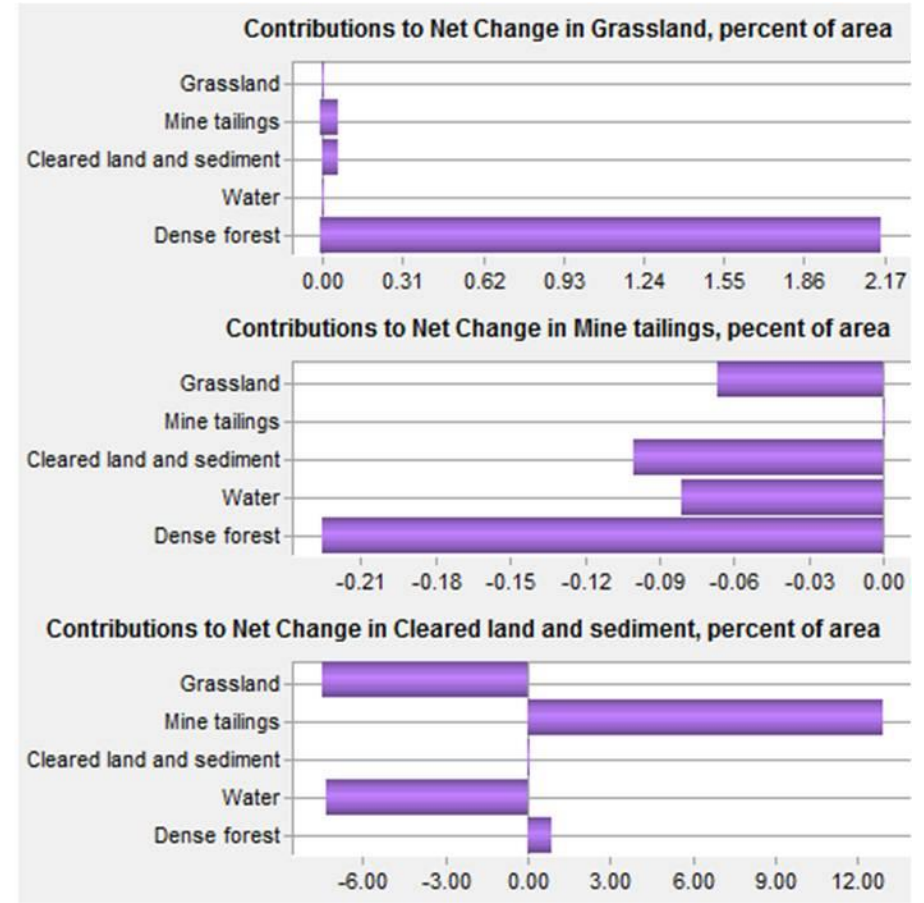
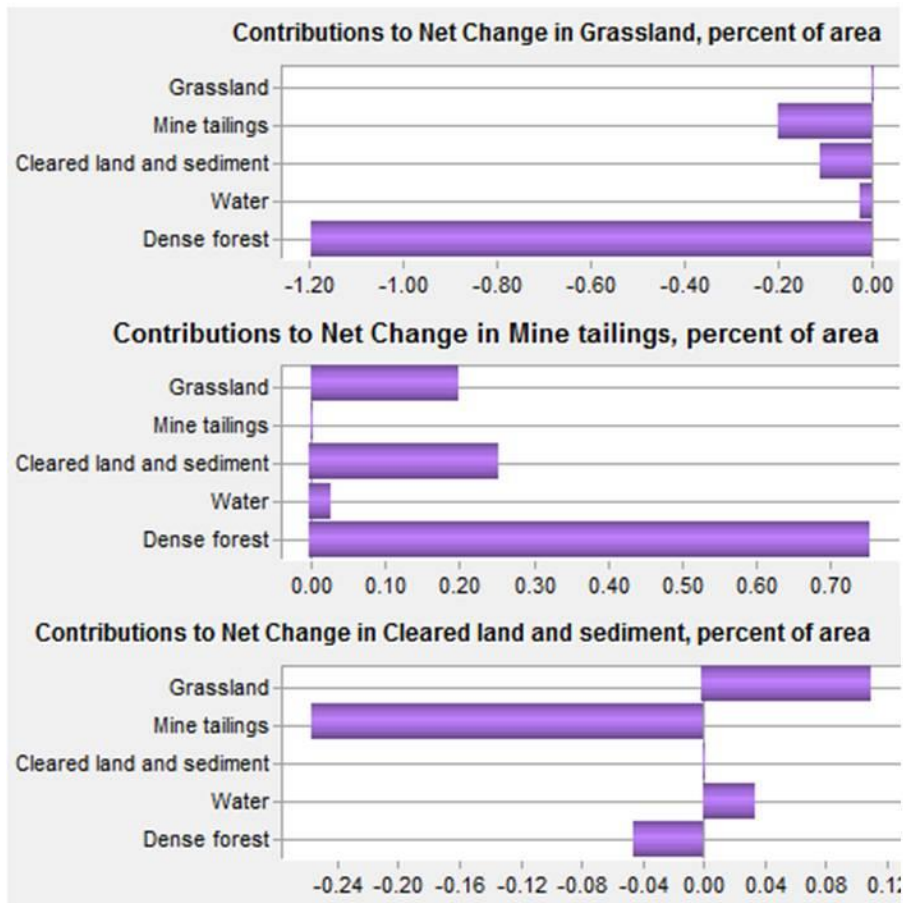


Figure 6: Contributions to net changes in categories of grassland, mine tailings, and cleared land and sediment in percent of total study area from 1986 to 1996 (left); and 1996 to 2006 (right).

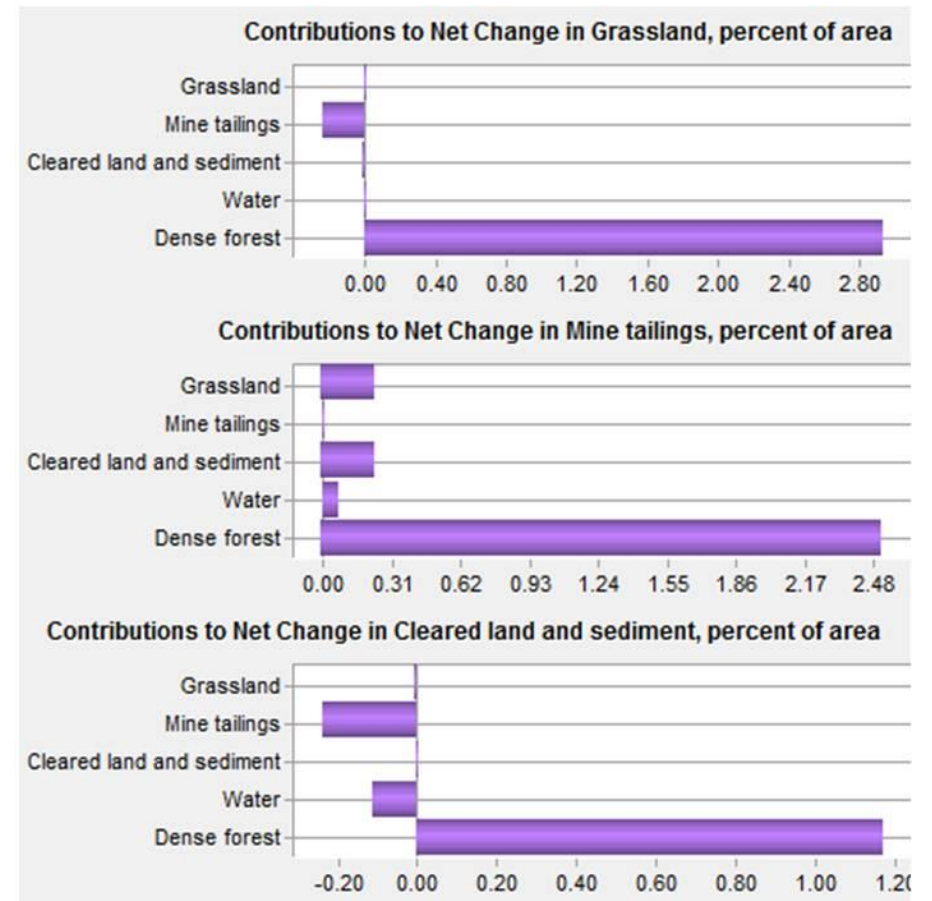
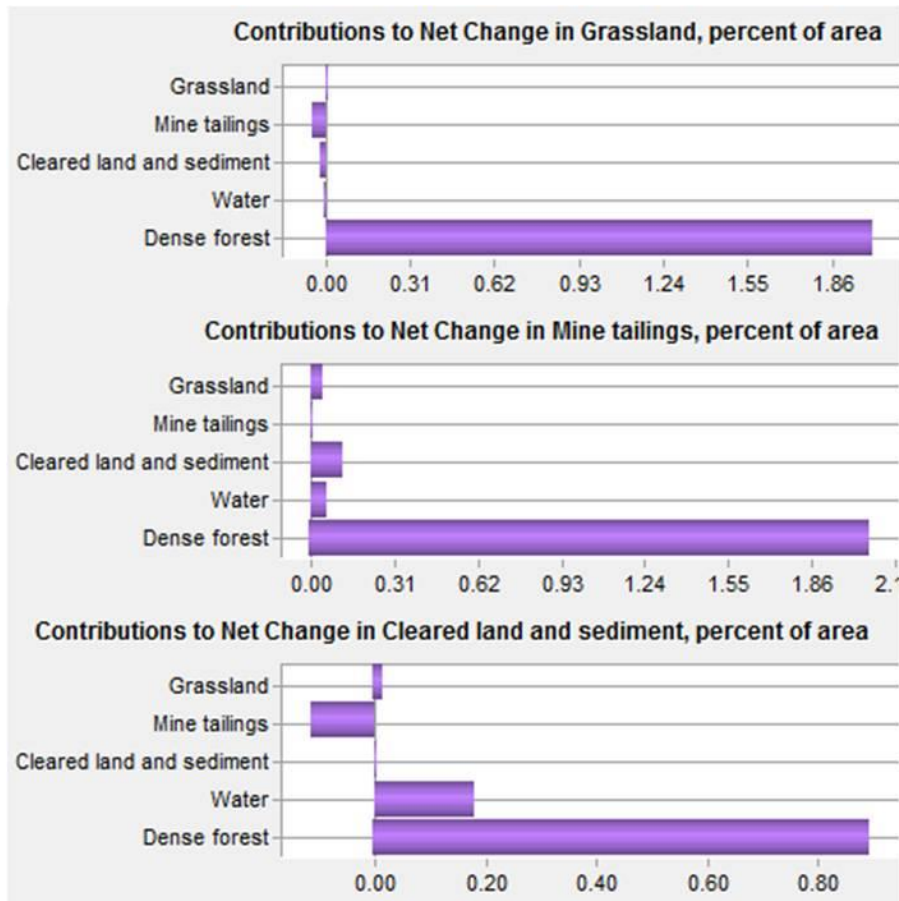


Figure 7: Contributions to net changes in categories of grassland, mine tailings, and cleared land and sediment in percent of total study area from 2006 to 2011 (left); and 1986 to 2011 (right).

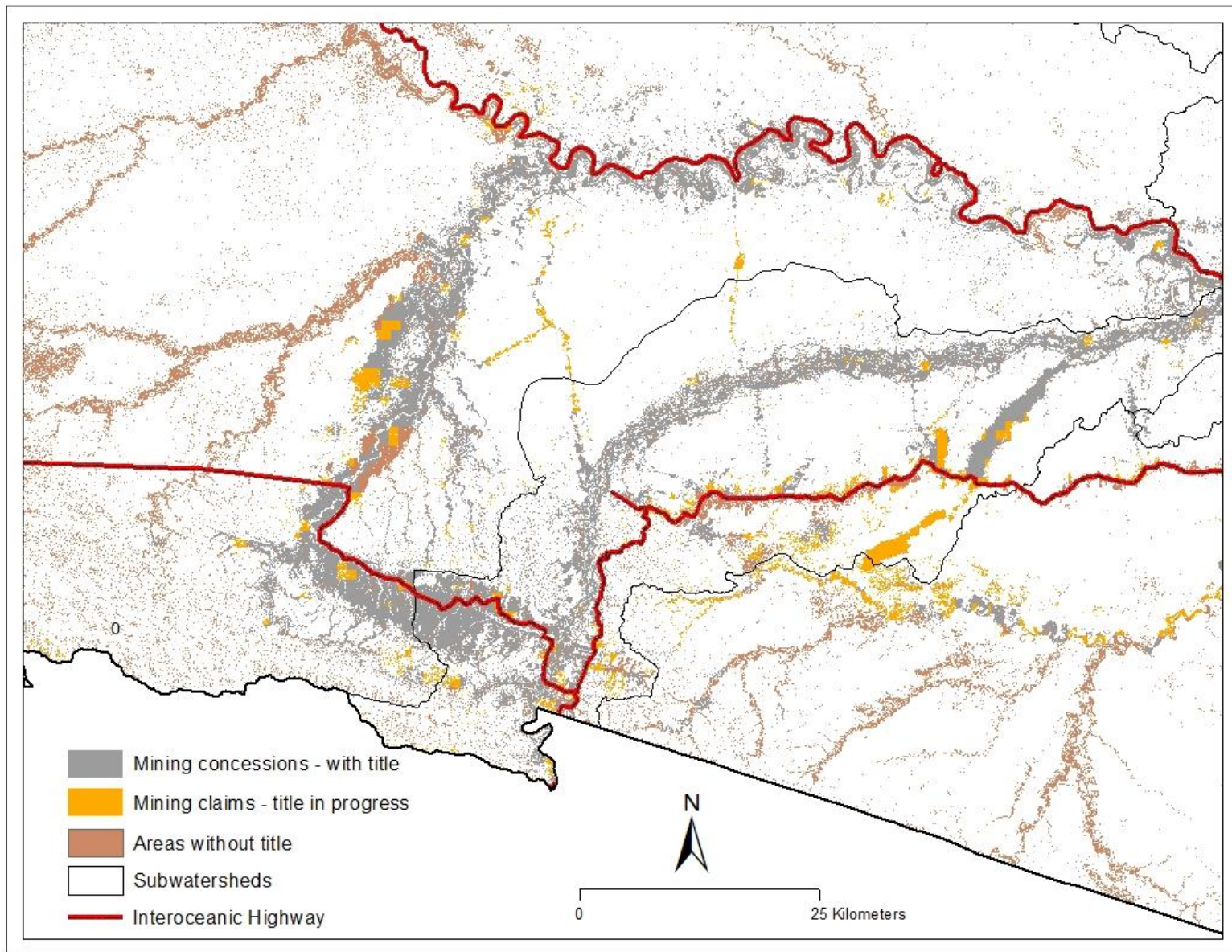


Figure 8: Map representing cumulative change between 1986 and 2011 in different ASM locations.

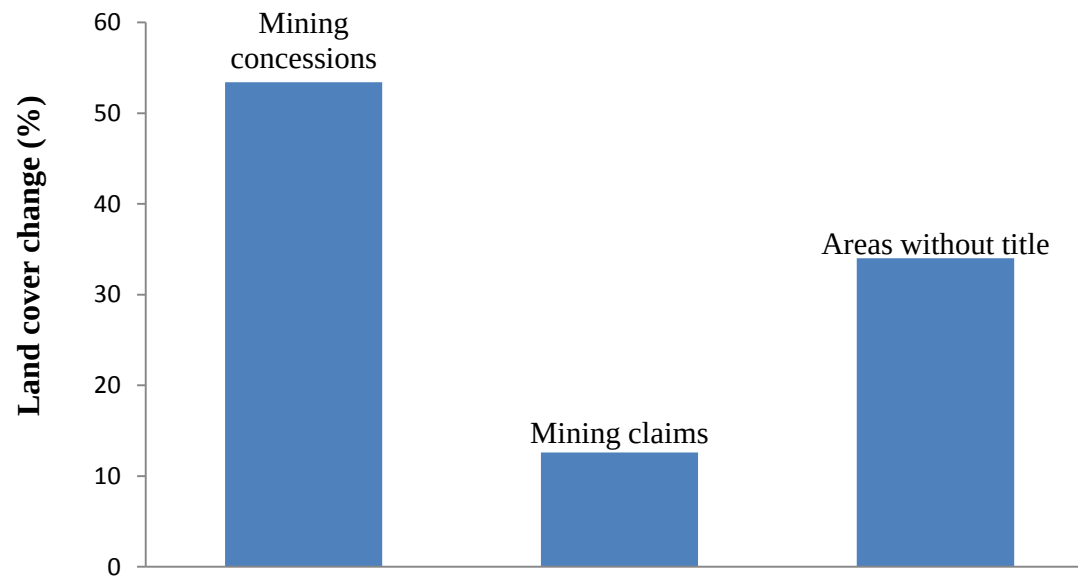


Figure 9: Proportion of land cover change caused by ASM.