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Chronosequence of Natural Regeneration in Abandoned Mining Sites in the Amazon Rainforest of Madre De Dios, Peru

Edson J. MORALES-PARRA[1,2*], Nobuyiki TANAKA[1], Martin PILLACA[3], Francisco ROMÁN-DAÑOBEYTIA[3,4] Luis E. FERNANDEZ [3,4] and Miles SILMAN [3,4]

[1]*Department of International Agricultural Development, Tokyo University of Agriculture, Tokyo, Japan*
[2]*Amazonian Scientific Innovation Center (CINCIA), Madre de Dios, Peru*
[3]*Geographic Information Systems Department, Amazonian Scientific Innovation Center (CINCIA), Madre de Dios, Peru*
[4]*Center for Energy, Environment and Sustainability and Department of Biology, Wake Forest University, NC 27106, USA*

*Corresponding author: morales.edsonjp@gmail.com

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Abstract: Gold extraction via small scale mining in the Amazon rainforest of Peru has become one of the greatest threats to deforestation and land degradation in the Amazon, especially in the Madre de Dios region which is one of the last biggest remnants of continuous tropical rainforest in the world. Restoration of these degraded ecosystems have become a priority in the last decade but without concrete actions, however, few research has been conducted in response to these restoration activities nor natural regeneration. The significance of this research was to study a chronosequence of natural regeneration in two active gold-mining sites in Madre de Dios-Peru (Paolita-PA; Santa Rita-ST) and how the nearby remnant forest contribute to natural regeneration. Sites were chosen depending on its management and the proximity to nearby remnant forest. Floristic composition of natural regeneration following abandonment of mining activities was studied by establishing a total of 12 plots (20x50m each), 6 with an abandonment period of 2 to 16 years and 6 were considered as reference forest. A total of 753 individuals from 44 families and 144 species were identified. To analyze biodiversity and similarity composition, Shannon and Jaccard indexes were used, respectively. The results showed that the abundance of species (Shannon) was higher in Paolita than in the Santa Rita mining site. From Jaccard's similarity index each mining site was analyzed in clusters finding that in Paolita, nearby remnant forest might not have a great influence over natural regeneration when compared with Santa Rita site which showed similarity between remnant forest, but instead the time of abandonment, availability of nutrients and forest fragmentation might be the cause of the recovery of degraded forest.

Keywords: Chronosequence, Natural regeneration, Gold mining, Amazon rainforest, Peru.

1. Introduction

The tropical rainforest is considered as one of the most biodiverse sites in the world (Connell, 1978) and the efforts of preserving these valuable ecosystems are highly important for the sake of humanity (Venter, et al., 2016). In the attempt of preserving the biodiversity, Peruvian amazon rainforest hosts various protected areas designate not only to preserve nature itself but also human populations. According to an official list of protected areas in Peru published by SERNANP (2019), only in the Region of Madre de Dios 3 National Parks, 1 National Reserve, and 2 Communal Reserves are part of the National Administration, and 25 Private Conservation Areas aim to preserve this great biodiverse ecosystem (Vuohelainen, et al. 2012). But despite these efforts, the region has face severe deforestation caused by agriculture, logging, cattle raising and gold mining (Román - Dañobeyta , et al., 2015) . A recent study (Caballero Espejo, et al., 2018) showed that from the years of 2010 to 2015, mining took the lead as cause of deforestation in the region and in a laps of 7 years (2010 – 2017) 64584ha were lost to gold mining. Given the current situation of deforestation and consecutively loss of biodiversity due mining, this study aimed to 1) conduct a chronosequence of secondary successional forest in active gold mining sites in the Region of Madre de Dios to analyze the response of forest after abandonment taking a close look into the floristic composition and structure, and 2) to analyze how remnant forest influence natural regeneration of nearby degraded lands. Thus, to accomplish our objectives, satellite images and aerial photographs were used for the site selection. To address biodiversity, Shannon's diversity Index was used (Kennard, 2016) and to analyze similarity between successional stages, Jaccard's similarity index was used.

2. Materials and Methods

Study area and site selection

The region of Madre de Dios is one of the 24 first-level administrative subdivisions of Peru. This region, part of the tropical rainforest, is located in the southeast side of the country neighboring Bolivia and Brazil, with an area of 85,182.63 km² and, divided into 3 provinces (Tambopata, Manu and Tahuamanu), is the third biggest region in Peru (Instituto Nacional de Estadistica e Informatica [INEI], 2017) According Holdridge (1966), 14 life zones are found and, notwithstanding the richness in biodiversity that this region holds (Gentry, 1988), it has been suffering the constant pressure of human activities such as cattle raising, agriculture, logging and mining (Venter, et al., 2016). Gold mining has increased rapidly in the region (Asner, et al. 2013, et al**)** and has become the main source of income for local and outer residents. This activity is mostly realized in a small scale, but it has led to a severe loss of forest cover, 6145ha/year (Román - Dañobeyta , et al., 2015).

To conduct this study the sites and plots were chosen based on two criteria: 1) managed by the same individual or organization and 2) early successional plots must had a considerable distance to remnant forest.

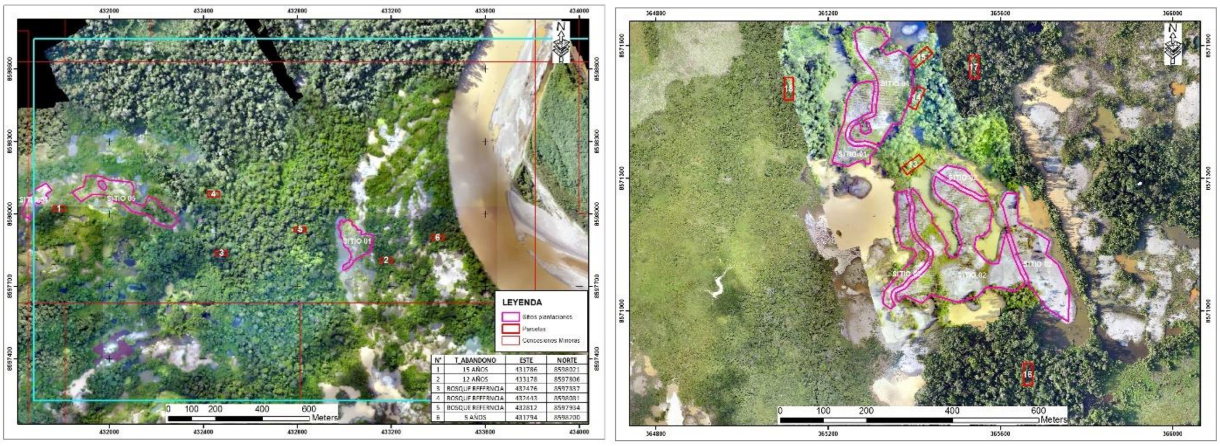


Figure 1: Aerial photos of Paolita mining site (left) and Santa Rita mining site (right).

Thus, following the first criteria, 2 sites were chosen (Figure1). The first was Paolita Mining Site, following the Madre de Dios River 30 minutes away from the town Laberinto which is located 45 minutes away from the capital of the region (Puerto Maldonado), and Santa Rita mining site, located in the buffer zone of the Tambopata National Reserve, adjacent to the Interoceanic Highway. Satellite images and aerial photos where used to stablish the plots.

The study area lies within two Landsat scenes (path-rows 02-69 and 3-69). A collection of all Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+)/Operational Land Imager (OLI) images with less than 40% cloud cover from archives of the United States Geological Survey (USGS) were used. This resulted in a collection of 68 Landsat images spanning 34 years from 1985 to 2017. With this results 6 plots, each one measuring 20mx50m (0.1ha), were randomly stablished at each site, giving a total of 12 plots (6 plots with an early stage of succession and 6 plots that served as reference forest) with an age after abandonment that goes from 2 to 18 years.

Data analysis

Each plot was given a name depending on the mining site. For Paolita mining site plots were named after the letter P and numbered from 1 to 6 been early stages of succession plots P1, P2 and P6, and old growth forest P3, P4 and P5. In Santa Rita mining site plots were named after ST and number from 13 to 18, where early successional plots were ST13, ST 14 and ST15, and old growth forest ST16, ST17 and ST18. For each plot, the total number of individuals was recorded as well as recognized to the maximum level classification (specie). Nomenclature were valeted and cross-checked using the Taxonomic Name Resolution Service v4.0 (Boyle, et al., 2013) and the website www.tropicos.org for double rectification. Diameter at breast height (DBH) of all seedlings equal or greater than 1cm was measured. For multi-stemmed individuals, each steam with a DBH $\geq$ 1cm was considered as one individual. Basal area of all species were computed. Diversity and similarity were measured with quantitative and qualitative indices (Kalacska, et al., 2004; Mora, et al., 2014). Thus, Shannon diversity index (H') and its respective evenness (E) was estimated (Kalacska, et al., 2004) and, for similarity analysis Jaccard’s similarity clustering was computed (Kennard, 2016).

3. Results and Discussion

Species composition

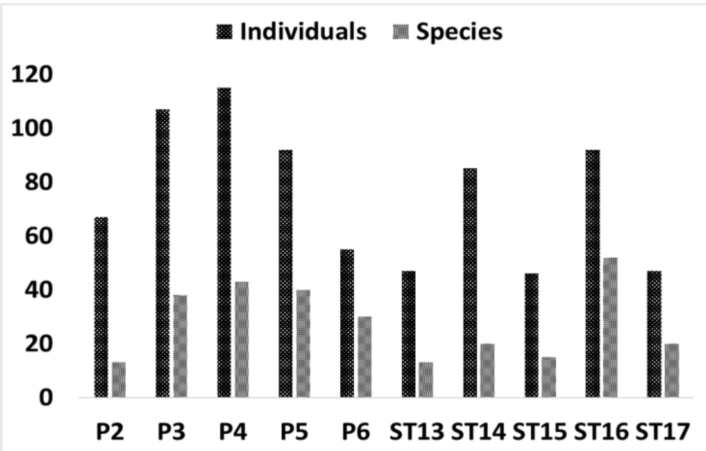
A total of 753 individuals were described in both sites, representing 144 species scattered in 44 families. The total number of individuals and species on each mining site were significantly different. At Paolita 436 individuals and 164 species were identified whereas at Santa Rita 317 individuals and 120 were found. The results showed a variation of species and individuals along the successional stage gradient as well as the dominance of some species. Number of individuals per plot and species composition was variable. It was expected (Wilkinson, 1999) that the number of seedlings of all species will decrease and become even as the stage of regeneration increases due its light demanding or shade tolerance. As other studies found (Peterson & Heemsker, 2001 and Liebsch , et al., 2008, et al.), it was confirmed that seedlings in old stages of regeneration were small in number compared with early stages. Early successional stages had a higher quantity of pioneer species and, although some pioneer species were found in remnant forest (P4&ST16) suggesting that at some point old growth forest were perturbated, results showed that there are some families exclusive to early and old stages (URTICACEAE and SAPOTASEA respectively) while others are present in all stages (MORACEAE). See Table 1. Stem density also changes along the years after abandonment together with dominance. For example, in Santa Rita mining site, plots with 8 years after abandonment(ST13&ST14), *Hieronyma alchorneoides* (Allemão) and *Guatteria megalophylla* (Diels) were the most representative species in early stages with a Relative Abundance (RA) equal to 20.83% and 25% respectively but, in the old grow forest the RA for both species changed significantly. Only one individual of *Guatteria megalophylla* (Diels) was found in both reference forest, and no natural regeneration of *Hieronyma alchorneoides* (Allemão) was found in old stages. In Paolita mining site, *Ochroma pyramidale* (Cav. ex Lam.) Urb. and *Cecropia pachystachya* Trécul were two of the most abundant species in plot P2 (2 years after abandonment) with a RA equal to 41.79% and 17.91% respectively but, as the forest matures in age (P6 = 6 years) the RA of both species changed dramatically (1.8% and 3.64% respectively) and these two were not found in old growth forest. Presence or absence of some species generally suggest that the area has been perturbed at some point of its successional growth. Pioneer species, such as *Hieronyma alchorneoides, Ochroma pyramidale* and *Cecropia pachystachya* are early successional species or pioneer species with rapid growth, low nutrient requirement but highly light requirement (Kennard, 2016). Also, basal area (Relative Dominance) will change across successional stages as seen in the results. Early stages in Santa Rita's plot ST13&ST15 had a Relative Dominance (RD) of 33.26% and 23.25% for *Cecropia pachystachya* Trécul and *Ocotea obovata* (Ruiz & Pav.) Mez respectively while plots in Paolita showed a RD of 49.99% and 19.81% for *Muntingia calabura* L. and *Zanthoxylum rhoifolium* Lam. respectively.

Table 1: Structure composition of families found in Paolita mining site (P) and Santa Rita mining site (ST). Plots are arranged from early successional stages (upper row) to old growth stages (downer row). Only families with a composition major or equal to 6% are represented in this table

	Family	Composition (%)	N◦ of species		Family	Composition (%)	N◦ of species
ST 13	MELASTOMATACEAE	27.08	1	**P2**	MALVACEAE	49.25	2
	PHYLLANTHACEAE	20.83	1		URTICACEAE	17.91	1
	URTICACEAE	18.75	1		MORACEAE	14.93	1
	MALVACEAE	12.50	2				
	EUPHORBIACEAE	8.33	1				
ST 14	ANNONACEAE	25.00	1	**P6**	FABACEAE	25.45	5
	PHYLLANTHACEAE	21.43	1		ANNONACEAE	16.36	2
	MELASTOMATACEAE	16.67	2		EUPHORBIACEAE	9.09	2
	APOCYNACEAE	11.90	1		MORACEAE	7.27	3
	EUPHORBIACEAE	7.14	3		URTICACEAE	7.27	3
ST 15	MELASTOMATACEAE	26.09	2	**P3**	MORACEAE	17.76	4
	ANNONACEAE	19.57	1		MYRISTICACEAE	14.95	2
	MALVACEAE	13.04	1		FABACEAE	11.21	5
	FABACEAE	10.87	4		ANNONACEAE	9.35	3
	PHYLLANTHACEAE	10.87	1		SAPOTACEAE	7.48	5
	CLUSIACEAE	8.70	1				
ST 16	FABACEAE	14.13	7	**P4**	MYRISTICACEAE	14.78	3
	ANNONACEAE	8.70	4		ANNONACEAE	13.91	3
	MELASTOMATACEAE	8.70	2		MORACEAE	12.17	6
	SAPOTACEAE	7.61	5		SAPOTACEAE	10.43	4
	MELIACEAE	6.52	2		MALVACEAE	7.83	2
					MELIACEAE	6.96	3
ST 17	MORACEAE	21.28	4	**P5**	MORACEAE	25.00	6
	MELASTOMATACEAE	19.15	1		ANNONACEAE	9.78	3
	POLYGONACEAE	17.02	1		MALVACEAE	9.78	3
	APOCYNACEAE	6.38	1		MYRISTICACEAE	8.70	3
	FABACEAE	6.38	3		SAPOTACEAE	8.70	3

Diversity and similarity measurements

Wilkinson (1999)proposed that immediately after the disturbance of an ecosystems, low levels of diversity is expected and as the successional stage increases, diversity will increase proportionally (Intermediate Disturbance Hypothesis). Not only our results agree with this hypothesis but also the results from several studies (Kalacska, et al., 2004; Mora, et al., 2014; Peterson,et al., 2001).



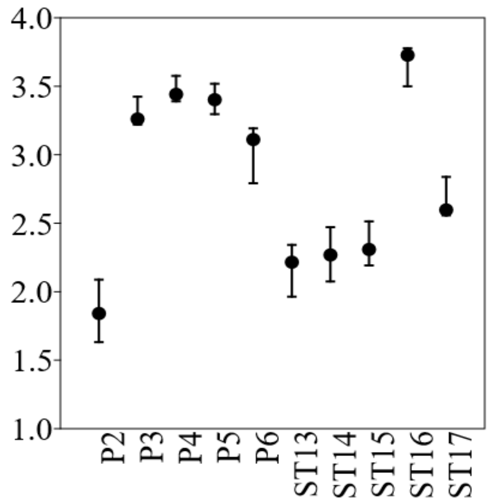


Figure 2: Paolita and Santa Rita's individuals and species composition (left). Shannon's diversity values of all plots (right)

As seen in Figure 2 and Table 2, Low levels of biodiversity, species and individuals were found in early stages and showed progressive increase over time. A significant difference in diversity was found not only within plots but also between mining sites (Paolita had higher diversity than Santa Rita mining site). In Paolita, the most resent disturbed plot (P2) showed the lowest level of diversity among all study plots, consecutively plot P6 (6 years successional stage) showed a remarkable diversity, almost similar of the remnant forest. Remnant forest showed in Paolita mining site showed an oscillation of diversity values as well as in its structural composition and, compared with Santa Rita mining site, early stages also presented low but increasing levels of diversity. When the data was computed, plot ST16 and ST17 (both old growth forest) presented a significant difference in diversity (ST16 = 3.73 and ST17 = 2.60). This significantly difference between these two old growth forest's diversity and number of individuals made us suggest that 1) although plots in Santa Rita are older than the stablished in Paolita and despite the fact that Santa Rita is located in the Tambopata National Reserve's buffer zone, the pressure over the land its proved to be higher (Asner et al. 2013)since its proximity to the Interoceanic Highway (Caballero Espejo, et al., 2018), 2) soil condition varies between sites and plots. Moran, et al. (2000) inicates that soil fertility greatly influences seccondary succession and that nutrients are stock in the vegetation rather than the soil itself. Thus, with a simple visual identification of soil properties, we found that soil in Santa Rita where secondary forest was present was sandy (Podzol) indicating that leaching of nutrients was hiegher. Therefore, having sandy soils and low nutrients avobe-ground gives as results less individuals and diversity with a slow recovery. Paolita, in the other hand, presented a different type of soil, where alluvial rocks were predominant, its proximity to the Madre de Dios river makes the soil much richer in nutrients which increases favorable conditions for the forest recovery (Jordan, 1985) even when disturbed. Plot P6 is an example of how fast the area could recover giving a great expectancy over P2 (2 years after abandonment) to follow the same trent (Liebsch, et al. 2008). Finally, 3) although both sites presented extreme pioneers, we proposed that nearby remnant forest accelerates recovery of disturbed areas and that the isolation of remnant forest and how far are located from the early stages could suggest lower or higher levels of diversity affecting recovery after disturbance.

Thus, to address this hypothesis we conducted a Jaccard's similarity clustering (Figure 3). This index was used to find floristic similarity between successional forest and old grown forest (Kalacska, et al., 2004). In the clustering graphic the similarity distance goes from 0 (0% of similarity) and 1 (100% similarity).

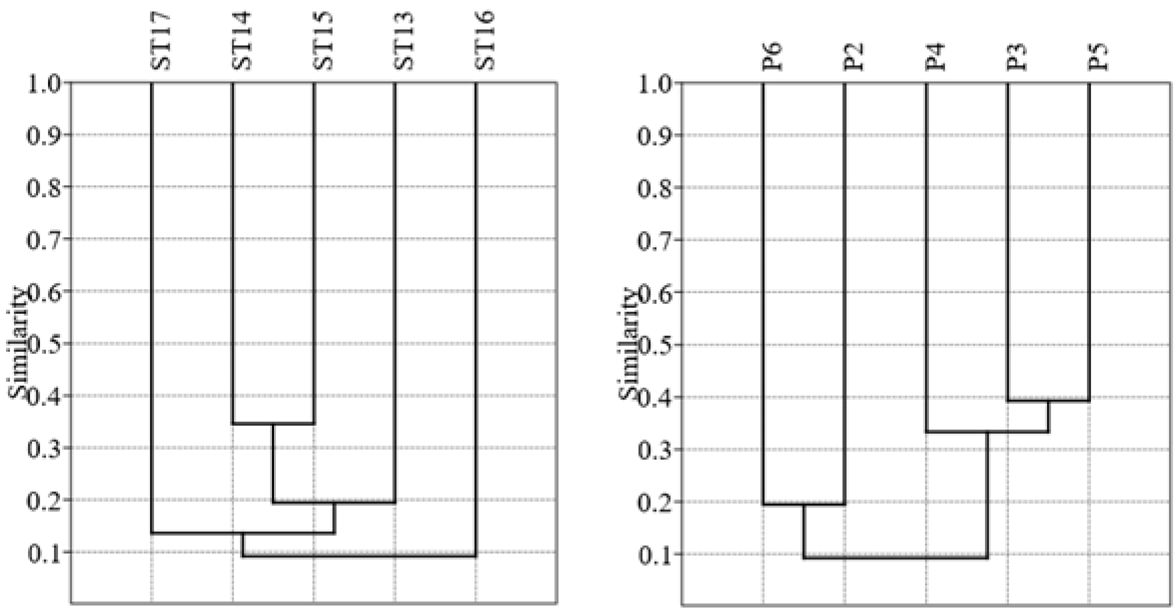


Figure 3: Jaccard's similarity clustering computed for both mining sites suggested that nearby remnant forest in Santa Rita has effect over natural regeneration over secondary succession.

Table 2: Detailed summary of data from Paolita and Santa Rita's plots indicate that as the successional stage of regeneration increases, levels of biodiversity increases in a proportional way.

Plots	SHANNON (H')	Evenness (J')	Individuals	Species	Years after abandonment
P2	1.84	0.72	67	13	**2**
P6	3.11	0.91	55	30	**5**
P3	3.26	0.90	107	38	**RF**
P4	3.44	0.92	115	43	**RF**
P5	3.40	0.92	92	40	**RF**
ST13	2.22	0.86	47	13	**8**
ST14	2.27	0.76	85	20	**8**
ST15	2.31	0.85	46	15	**15**
ST16	3.73	0.94	92	52	**RF**
ST17	2.60	0.87	47	20	**RF**

Thus, clustering analysis showed that the closest similarity between early successional stage (P6) and old grown forest (P4) was 18%, both plots 713m away from each other, and the less similarity was found between P2 (early successional stage) &P3 (old growth forest), these two plots were 100% dissimilar and both plots 616m away from each other. For Santa Rita the closes similarity was found between plot ST17&ST15 (old growth forest and early stage respectively) with a similarity equal to 18%, both plots 124m away from each other, and the lest similarity was found between plots ST13&ST16 with a similarity equal to 2%, both plots 544m away from each other. From these results we could corelate diversity and similarity between plots at each site. Even though in both sites, the closest similarities between early stages and old growth forest is the same (18%) and considering the distance between plots, suggest that there is no significant influence of remnant forest over species composition and recovery in Paolita since these plots (P6&P4) are considerably far from each. This observation has relation with the study presented by (Tabarelli, Mantovani, & Peres, 1999) on how fragmentation affects diversity. Another factor for boosting the recovery observed in Paolita might be caused by the Madre de Dios river itself which could serve as a natural corridor for seed dispersal (Tewksbury, et al., 2002) and, following the same statement, in Santa Rita mining site, similarity between plots ST17&ST15 suggest that remnant forest has influenced over the recovery of early stages of regeneration due its proximity from each other but, considering that ST17 has a low diversity level and the forest fragmentation is considerably higher, it also caused a low-diversity regeneration present in early stages, even when plots in this area are older than those stablished in Paolita.

4. Conclusion

The impact produced by gold mining over forest lost has been studied previously by Caballero Espejo, et al., (2018) and several reforestation trials have been conducted in the last decade (Román - Dañobeyta , et al., 2015). Between 1987 and 2017 nearly 100,000ha of forest were lost and, as seen during the process of making this paper, it is more likely that this number has already been surpassed. Ecological restoration is far to be accomplished due the severity of the degradation not only above-ground but soil itself. Results proved that forest regeneration could be achieve in at least 6 years after abandonment as seen in Paolita (Table2) but we must consider that there are several factors that might and might not boost natural regeneration although nature has a high resilience over disturbances; severe deforestation, forest fragmentation and soil condition directly affects natural regeneration. We might conclude that nearby remnant forest might not have a direct influence over regeneration as results from Paolita showed (Figure 3), but instead several factors influence the recovery of degraded tropical forest. For a deeply understanding of the recovery of degraded forest, the addition of some other factors (seed bank, proximity of remnant forest to the degraded area, etc.) is required. This study focused on the passive ecological restoration of the tropical rainforest ecosystem. There are some studies that proposed different approaches of restoration or reforestation (Attiwill, 1994; Romell, et al., 2008, Pereira, et al., 2008; et al.) but given the scale of deforestation seen in Madre de Dios, a holistic approach that include stakeholders and other actors as part of the restoration of this valuable ecosystem is needed.

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