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Agroforestry as a post-mining land-use approach for waste deposits in alluvial gold mining areas of Colombia

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ABSTRACT

Alluvial gold mining generates a vast amount of extractive waste that completely covers the natural soil, destroys riparian ecosystems, and negatively impacts river beds and valleys. Since 2002, a gold mining company has striven to create agroforestry plots in the waste deposits as a post-mining management approach, where agricultural crops and livestock are combined to complement reforestation in the area. This research aims at supporting reclamation of waste deposits by providing a comprehensive understanding of processes to manage the transition of nutrient-poor and acidic deposition sites towards productive agroforestry-based systems. Major components of this research comprise (i) an analysis of environmental and social challenges of the gold mining sector in Colombia, and its potential opportunities to add value to affected communities, (ii) an assessment of management practices and decision-making processes of the farmers working on reclamation areas, (iii) an analysis of the sources of variability of waste deposits from the perspective of soil development and vegetation succession, (iv) an analysis of spatial variability of the physicochemical properties of waste deposits with a spatially explicit management scheme, and (v) an assessment of vegetation recovery in terms of biomass and plant community composition.

Farmers who are currently working on areas undergoing reclamation rely mostly on their own local knowledge to respond to the challenges that the heavily disturbed conditions of the area pose to crop establishment. Therefore, increasing their awareness of the inherent heterogeneity of their fields, as well as the interdependencies between management practices and improvement of soil fertility, may increase the productivity of their farms. The analysis of sources of variability of the waste deposits generated by alluvial gold mining revealed that these deposits are primarily influenced by the parent material of the alluvial gold deposits and by the technology used for gold mining (bucket or suction dredges), which define the type of deposit formed (gravel or sand). Waste deposits can provide essential functions for rural areas such as woody biomass production and crop establishment if deposits are managed according to a specific purpose, and crop selection for each deposit is done based on physicochemical and structural soil properties. This finding is echoed by the spatial assessment of vegetation reestablishment through the combination of remote sensing with machine-learning techniques that show a high spatial variability of textural properties and nutrient contents of the deposits. A management approach is proposed with the use of delineated management zones, which can lead to an overall increased productivity by developing strategies suitable to the characteristics of each field and its potential uses.

Agroforstwirtschaft als Landnutzungsansatz auf Abraumdeponien in alluvialen Goldabbaugebieten Kolumbiens

KURZFASSUNG

Der Abbau von alluvialem Gold erzeugt eine große Menge mineralischen Abfalls, der den natürlichen Boden vollständig bedeckt, Uferökosysteme zerstört, und Flussbetten und -täler negativ beeinflusst. Von einem Goldminenbetreiber werden seit 2002, als ein Ansatz einer Postbergbaustrategie, Agroforstparzellen in Abraumdeponien angelegt. In diesen werden landwirtschaftliche Nutzpflanzen und Viehhaltung zur Aufforstung der Parzelle kombiniert eingesetzt. Diese Forschungsarbeit beabsichtigt die Rekultivierungsmaßnahmen in Agroforstparzellen durch ein umfassendes Verständnis der beteiligten Prozesse zu unterstützen und den Übergang von nährstoffarmen und sauren Abraumdeponien hin zu produktiven agroforstbasierten Systemen zu steuern. Die Hauptbestandteile dieser Arbeit umfassen (i) eine Analyse der ökologischen und sozialen Herausforderungen des Goldminensektors in Kolumbien und potenzielle Möglichkeiten einen Mehrwert für die betroffenen Gemeinden zu schaffen, (ii) eine Bewertung der Managementpraktiken und Entscheidungsprozesse der Landwirte im Rahmen der Rückgewinnung von Landnutzungsflächen, (iii) eine Analyse der Ursachen von Varianz zwischen Abfalldeponien aus der Perspektive der Boden- und Vegetationsentwicklung, (iv) eine Analyse der räumlichen Variabilität der physikochemischen Eigenschaften von mineralischen Abraumdeponien mit einem räumlich expliziten Managementschema und (v) eine Bewertung der Vegetationserholung im Sinne der Zusammensetzung von Biomasse und Pflanzengemeinschaften.

Landwirte die in Gebieten arbeiten die gegenwärtig einer Rekultivierung unterzogen werden, verlassen sich größtenteils auf ihre lokalen Erfahrungswerte, um mit den Herausforderungen für die Nutzpflanzenproduktion umzugehen, die durch die stark gestörten Bodenbedingungen verursacht werden. Eine Steigerung des Bewusstseins der lokalen Farmer für die inhärente Heterogenität ihrer Felder, sowie der Interdependenzen zwischen Managementpraktiken und der Verbesserung der Bodenfruchtbarkeit, kann die Produktivität der Farmbetriebe erhöhen. Die Analyse der Variabilitätsquellen der durch den alluvialen Goldabbau entstandenen mineralischen Abfalllager ergab, dass diese Lagerstätten in erster Linie vom Grundgestein der alluvialen Goldlagerstätten und der verwendeten Abbautechnik (Schaufel- oder Saugbagger) beeinflusst werden. Diese Faktoren bestimmen die Art der gebildeten Ablagerung (Kies oder Sand). Abfalldeponien können wesentliche Funktionen für ländliche Gebiete wie die Produktion von Holzbiomasse und den Anbau von Nutzpflanzen ermöglichen, wenn die Lagerstätten einem bestimmten Zweck entsprechend bewirtschaftet werden und die Auswahl der Kulturen für jede Lagerstätte auf Grundlage der spezifischen physikochemischen und strukturellen Bodeneigenschaften erfolgt. Dieser Befund wird durch die räumliche Bewertung der Vegetationsneubildung durch die Kombination von Fernerkundung mit maschinellen Lerntechniken bestätigt, die eine hohe räumliche Variabilität der Textureigenschaften und Nährstoffgehalte der Deponien zeigt. Es wird ein Managementansatz vorgeschlagen, bei dem abgegrenzte Bewirtschaftungszonen unterteilt werden. Dies kann zu einer insgesamt höheren Produktivität führen, indem Strategien entwickelt werden, die den Eigenschaften jedes einzelnen Feldes und seiner potenziellen Nutzungsmöglichkeiten entsprechen.

DEDICATION

This dissertation is dedicated to my family whose love and blessings hearten my life every day.

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1. SUMMARY

Gold mining is considered as a potential axis of development in Colombia. Yet there is a common perception that the expansion of gold mining may cause environmental and health impacts, competition for land and water, and loss of livelihood opportunities for farmers. Alluvial gold mining in Colombia generates a vast amount of deposits that completely cover the natural soil, destroy riparian ecosystems and impact river beds and valleys. The latest inventories reveal that approximately 79,000 ha are affected by alluvial gold mining in the country (UNODC, 2016), and 80% of this land located in the department of Antioquia. Deposits created by alluvial gold mining usually have low levels of macronutrients and an acidic pH, which tend to disrupt soil formation processes and plant growth. There is also a discontinuity between upper and lower profiles of the soil due to the superposition of the waste over the natural soil.

Since 2002, a gold mining company has striven to create agroforestry plots in the waste deposits as a post-mining management approach for alluvial gold mining areas of the municipalities of Nechi and El Bagre, Antioquia. The aim is to restore the vegetative cover of the wasteland while supporting settlers through the establishment of farmland with integrated trees and shrubs. In these agroforestry systems, agricultural crops and livestock are combined to complement reforestation in the area. More than 600 ha have been so far reclaimed using this approach. Three agroforestry plots have been established each year since 2002. The process begins with the entitlement of the land to the farmer. The mining company provides construction materials and manpower for the construction of the house, basic sanitation facilities, water and wastewater treatment systems, as well as the provision of seeds and seedlings for the establishment of tree and crop plantations.

Although this reclamation process has been going on since 2002, there is still little understanding of the intrinsic factors associated with the nature of the deposits that might hinder the re-establishment of the vegetation cover or affect crop productivity. This research aims to provide a comprehensive understanding of processes to manage the transition of nutrient-poor and acidic deposition sites towards productive agroforestry-based systems. This includes the question of the main sources of variability of the waste deposits from the perspective of soil development and vegetation succession, with emphasis on spatial variability of deposit properties and its implications for crop management and reforestation. Drawing on information gathered from field research that took place between 2015 and early 2017 in the area undergoing reclamation in the municipality of El Bagre, the main objective of this study is to investigate how management practices and decision-making processes concerning crop and livestock production and reforestation can be adapted to respond to the considerably varying quality of the land to optimize productivity, as well as to understand the extent and patterns of variability of the waste deposits.

The introductory chapter presents an analysis of the main environmental and social challenges of the gold mining sector in Colombia, as well as of the current initiatives that are being developed to cope with these challenges and potential opportunities to mitigate the negative impacts of gold mining while adding value to affected communities. The main findings suggest that, despite many drawbacks and an often negative image, gold mining has the potential to confer economic benefits to some communities. It is thus necessary to develop effective regulatory frameworks that aim to reduce informality of gold mining, provide guidelines to plan and design environmental management plans, develop safety regulations for mining activities, and protect biodiversity hotspots. Reclamation practices are of utmost importance as a coping strategy for affected communities, therefore a deeper understanding of the needs of the communities is crucial for decision making regarding post-mining land use.

Chapter 3 presents an assessment of management practices and decision-making processes of the farmers working on the reclamation of these areas with respect to crop and livestock production, as well as of their strategies to deal with the heterogeneity of their fields. For this assessment, semi-structured surveys were

conducted with farmers currently working on areas undergoing reclamation, and soil samples were collected according to the farmers' perception of soil fertility. Farmers rely mostly on their own local knowledge to respond to the challenges that the heavily disturbed conditions of the area pose to crop establishment. Their understanding of the complexity of their fields influences their management practices, therefore increasing farmers' knowledge about the inherent heterogeneity of their fields, as well as the interdependencies between management practices and improvement of soil fertility, may be a good strategy to increase the acceptance of management guidelines provided by extensionists. The creation of spaces that promote cooperation between more experienced farmers and farmers who are starting with the restoration process will enrich and facilitate the adaptation of management strategies. The findings also imply that the expansion of extension services and education opportunities for farmers in the area is required, not only to provide support to the farmers but also to create cooperation of farmers with scientists working in the area.

Chapter 4 focuses on the analysis of the sources of variability of waste deposits from the perspective of soil development and vegetation succession. Through analysis of soil samples and vegetation surveys, it is shown that waste deposits are primarily influenced by the parent material of the alluvial gold deposits and by the technology used for gold mining (bucket or suction dredges) that define the type of deposit formed (gravel or sand). Furthermore, these deposits can ensure essential functions for rural areas such as woody biomass production and crop establishment if gravel or sand deposits are managed according to a specific purpose, and crop selection for each deposit is based on physicochemical and structural properties. It is a challenge for the farmers living in the study areas to identify management strategies and areas where crop yield is not significantly affected by the quality of the substrate. However, some unfavorable soil properties can be compensated for through the application of special ameliorative measures and the adoption of crop growing technologies, yet it is difficult to compensate for crop limiting factors such as soil texture, stoniness and gravel content.

In Chapter 5, an analysis of the spatial variability of the physicochemical properties of the deposits is presented along with a spatially explicit management scheme. Spatial variability was studied using a geostatistical approach, and a vegetation index was used as a proxy of productivity to correlate deposit properties with the potential productivity of the deposits. The results show that the areas have a predominantly low pH, and in spite of the high contents of nitrogen and organic matter, there is a lack of nutrients over almost the entire area. Due to the high spatial variability of textural properties and nutrient contents of the deposits, a management scheme was proposed based on delineated management zones, which can lead to an overall increased productivity by developing strategies suitable to the characteristics of each field and its potential uses.

Chapter 6 deepens the analysis of sources of variability with an assessment of vegetation recovery in terms of biomass and plant community composition. To achieve this, a series of multispectral images captured by an unmanned aerial vehicle was correlated with field measurements of vegetation using machine learning techniques. The findings show that areas covered by gold mining waste can be successfully recovered and converted into productive ecosystems if appropriate management strategies are adopted to increase biomass, maximize productivity and promote an increased tree species diversity of the areas undergoing reclamation. To achieve this, special attention should be paid to fallow periods, management intensity and landscape configuration of these areas. In addition, the selection of tree species for the agroforestry systems should aim to minimize the use of invasive species, and promote the use of native species that improve the resilience of the newly created ecosystems.

Chapter 7 presents the main conclusions and outlook of the study. It is concluded that agroforestry can be a suitable post-mining land-use approach for waste deposits in gold mining areas of Colombia. Waste deposits have the capacity to sustain

agroforestry systems and to provide the substrate for the growth of trees, crops and grasses. However, the long-term sustainability of these agroforestry systems may highly depend on developing management practices adapted to the high heterogeneity of these deposits, so that decisions regarding fertilization, species selection for plantations, and identification of areas for crop establishment is done based on the highly varying properties of the deposits. Furthermore, biodiversity restoration needs to be considered as a success indicator in addition to the restoration of the vegetation cover and biomass increase.

2. GOLD MINING AS A POTENTIAL DRIVER OF DEVELOPMENT IN COLOMBIA: CHALLENGES AND OPPORTUNITIES[*]

Abstract

The Colombian government included gold mining as one of the drivers of development for the period 2014 – 2018. Large-scale gold mining is expanding due mainly to international investors attracted by the government. Small-scale and artisanal mining is also expanding, mainly because of increasing gold prices. This expansion of gold mining activities can have considerable consequences for the environment, as it can lead to more pollution and environmental degradation, posing a threat to the natural ecosystems and the health of the communities living in gold mining areas. This literature review analyzes the main challenges of the gold mining sector in Colombia from the environmental and social perspective, as well as initiatives developed to cope with these challenges and the opportunities to carry out more sustainable gold mining activities in the country.

The main environmental challenges of the gold mining sector in Colombia are the pollution of natural ecosystems through the generation of solid waste, emissions of mercury during gold amalgamation, and greenhouse gas emissions. To cope with these challenges, reclamation of waste deposits is being conducted through silviculture, agriculture and reforestation. Furthermore, mercury reduction technologies have been adopted in gold mining areas and trials for remediation of polluted ecosystems are being conducted. The main social challenges of the gold mining sector are high levels of poverty, illegality and violence of communities living in the gold mining areas, as well as high levels of informality of gold mining. To cope with these challenges, the communities are being actively involved in the reclamation schemes of gold mining companies in many areas of the country with the aim to restore their livelihoods and improve their

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[*] This chapter was submitted to the Journal of Cleaner Production (https://www.journals.elsevier.com/journal-of-cleaner-production/). Currently under review.

wellbeing. Moreover, elements of corporate social responsibility are being implemented to compensate for the loss of livelihoods, health effects and other social consequences of gold mining activities. To achieve a more sustainable gold mining production in the country, it is necessary to develop a framework for sustainability assessments to support decision making in the sector. Efforts need to be made to improve resource-use efficiency and biodiversity protection. From the social perspective, corporate social responsibility practices should be strengthened, especially towards understanding the needs of the local communities and the creation of mechanisms of participation that could help to prevent social conflicts around gold mining areas.

2.1 Introduction

The colonial era in South America brought an expansion of mining for gold, silver and other metals (Erlick, 2014). Exploration in Colombia started in the mid-1530s. By 1544, mining was well established in the region of the Upper Cauca River, and by 1547 the Spaniards already had knowledge of rich gold deposits located 600 km upstream of the Cauca River. As the deposits were discovered, they were intensely exploited and promptly depleted (Acemoglu et al., 2012). To increase the yield of the precious metal, several techniques were introduced, including hazardous processes such as mercury amalgamation, which is still practiced today.

The distribution of the gold deposits in Colombia is determined through the geomorphological features of the northern Andes. The most important gold deposits are concentrated in three regions between the Western and Central Cordilleras, in the drainage basin of the Cauca River, the upper Magdalena valley between the Central and Eastern Cordilleras, and the lowlands of the Pacific coast (Acemoglu et al., 2012). The north-west part of the country, i.e. the departments of Antioquia and Choco, has yielded the most significant gold outputs over the last 10 years, with around 40% and 25% of the total national production, respectively (SIMCO, 2017).

Currently, the gold mining sector in Colombia is formed by three main subsectors: large-scale formal, small-scale, and artisanal mining. Artisanal mining refers to panning in rivers to separate gold grains from the sand, or using picks to extract gold-laced earth. Small-scale mining involves more machinery and affects larger areas. Small inflatable floats, fitted with pumps and hoses, are used to perform alluvial mining. Homemade explosives are used to blast shafts to explore underground deposits. Large-scale mining employs the most engineered exploitation methods, with higher industrial security, skilled labor, higher working capital level, and larger funding sources, which makes it the most competitive type of mining. Artisanal and small-scale mining is increasing due to the rising price of gold, which despite the downward trend between 2012 and 2015, in 2016 remained approximately 3-fold higher than in 2000 (World Gold Council, 2016).

Artisanal gold mining is also a source of income for the rural population and usually performed without technical assistance in a very rudimentary fashion that often involves the use of toxic substances like mercury for ore concentration. The common perception of the affected communities in the rural areas is that the expansion of industrial gold mining results in competition for land and water, pollution with cyanide and heavy metals, displacement of communities, and loss of livelihood opportunities for farmers and artisanal miners (Specht and Ros-Tonen, 2016).

The fact that 20% of the Colombian municipalities have gold deposits has drawn the attention of national and international companies (World Gold Analyst, 2011). In the last decade, international investors were attracted by the Colombian government, which envisions the gold sector to be a key driver for the economic development of the country (Rudas, 2013). Colombia plans to increase foreign direct investment (FDI) in gold mining from the present US$ 0.4 to 4.5 billion and to double gold production until 2025. One of the most important international players here is AngloGold Ashanti (Table 2.1). It has been granted a concession for the exploration of *La Colosa* in the mountains of Tolima, with a foreseen investment of US$ 100 million and expected gold reserves of 384.4 tons. Canada's Greystar Resources is planning to invest US$ 40 million in the Angostura gold project, and Medoro Resources have acquired several national gold companies such as Frontino, Mineros Nacionales, and Colombia Gold for >US$ 100 million (Siegel, 2013).

Table 2.1. Most important gold mining projects of foreign companies in Colombia.

Company	**Name of mine**	**Investment sum**	**Country**	**URL**
AngloGold Ashanti	Gramalote La Colosa	USD 255 million by 2013	South Africa	http://www.anglogoldashanti.com/en/About-Us/Regionsandoperations/colombia/Pages/default.aspx
Batero Gold Corp	La Cumbre Quinchía	NA	Canada	http://www.baterogold.com/es/dep%C3%B3sito-la-cumbre
Newrange Gold Corp	Anori-Porce Rionegro Yarumalito Mercedes El Dovio	USD 52.9 million by 2014	Canada	http://www.newrangegold.com/home.asp
Colombia Crest Gold Corp	Fredonia Venecia	CAD 100.6 million by 2013	Canada	http://colombiacrestgold.com/_resources/presentations/CLB_December_2013.pdf
Continental Gold Ltd	Buritica	USD 155.5 million by 2016	Canada	http://www.continentalgold.com/en/investors/presentations/
Galway Resources Ltd	Vetas	NA	Canada	http://www.galwaygoldinc.com/s/Vetas.asp
Gran Colombia Gold Corp	Zancudo Marmato Segovia	NA	Canada	http://www.grancolombiagold.com/Home/default.aspx

Company	**Name of mine**	**Investment sum**	**Country**	**URL**
Ecooro	Angostura	NA	Canada	http://www.eco-oro.com/s/Angostura.asp
Miranda Gold Corp	Cerro Oro Oribella Antares	NA	Canada	http://www.mirandagold.com/s/WhyColombia.asp

NA: Not available

Although the contribution of metal mining to the Colombian gross domestic product (GDP) in the past has been rather limited with 0,41% (2011), 0,46% (2012), 0,40% (2013), and 0.35% (2015) (Erlick, 2014; Ministerio de Minas y Energia, 2015), its share is expected to substantially increase by 2025. Due to the complexity of mining activities, it is difficult to estimate the proportion of gold production by legal or illegal mining. Companies affiliated with the Association of Large-Scale Mining contribute only 12% to the total national gold production, which constitutes a huge challenge for the Colombian government (Bernal, 2016).

Gold mining is an essential source of income in a number of developing regions, where the opportunities for economic activities are limited (Hinton et al., 2003). Economists consider that mining is the vehicle to drive sustained economic growth in developing countries, as in the past it was the main driver for growth and industrialization in countries such as Canada, USA and Australia (Whitmore, 2006). However, Power (2002) argues that when the development of mining activities occurs in a context of underdeveloped social, political and economic institutions, the wealth produced by the exploitation of the non-renewable resource tends to be misspent, the level of social conflict increases and nearly irreparable damage is inflicted on the environment. All of this together might leave a developing nation permanently poorer (Power, 2002). Therefore, considering the growth of an extractive industry as a potential driver for development requires careful consideration before making final conclusions about the extent of expected net benefits or inherent costs.

Literature on gold mining in Colombia can be found on the topics of gold prospecting (Horner et al., 2016), deposit formation (Madrid et al., 2017; Naranjo-Sierra et al., 2016), gold mining and exploitation (Fuller and Bygness, 2014) from different perspectives, i.e. historical (Brown, 2012), environmental sciences (Marrugo-Negrete et al., 2017; Salazar-Camacho et al., 2017), medical (Castellanos and Leon, 2010; Rodríguez-Villamizar et al., 2015), engineering (Álvarez et al., 2014; Bustamante et al., 2016), social science (McNeish, 2017; Rettberg and Ortiz, 2016) and also violation of human rights (Powell, 2015). This illustrates the broad spectrum of topics that have been covered by researchers in the past. However, with the exception of some recent literature that analyzes new perspectives of the gold mining sector in the country, few authors have sought to unify the various dimensions of gold mining in Colombia under the over-arching theme of economic growth and development.

This literature review was conducted to gain an overview of previous research in the gold mining regions of Colombia for the assessment of environmental and social impacts of gold mining activities in the involved communities. Against this background, this review aims to identify current initiatives created by researchers, the community, the government and international organizations to cope with the impacts of gold mining activities from the environmental and social perspective. Furthermore, this review identifies some opportunities for improvement for the gold mining sector in the country from the perspective of the development of communities in mining areas in an environmentally sustainable and socially sound way.

2.2 Methodology

The methodology followed for the elaboration of this literature review was based on the tasks proposed by Fink (2013) (Figure 2.1). The first task consisted of the selection of the research questions aimed to guide the review in order to understand the current challenges, initiatives and opportunities of the gold mining sector in Colombia. The following research questions were defined:

- What are the main environmental and social challenges that the gold mining industry currently faces in Colombia as a potential promoter of development in the country?
- What are the current initiatives that are being conducted to face these challenges?
- What are the main opportunities for improvement for the gold mining sector of the country from the perspective of the development of communities living in gold mining areas?

In a second step, terms were selected for the search in databases and search engines. The following search strings were selected for an initial screening of general information on gold mining in Colombia:

“_gold”_ AND _(“mining” OR “mine”_ OR _“mines”)_ AND _(“Colombia”)_

After the general screening, specific terms that were considered of high importance for this literature review were included:

(“min*” OR “mine” OR _“mines”)_ AND _(“Colombia”)_ AND (“_mercury_” OR “_cyanid_*” OR “_waste_”)

(“min*”) AND _(“Colombia”)_ AND (“poverty” OR “_illegal_*” OR “_violence_” OR “_educat_*” OR “_informal*_”)

(“min*”) AND _(“Colombia”)_ AND (“_reclam*_” OR “_revegetat_* OR _restor_*)

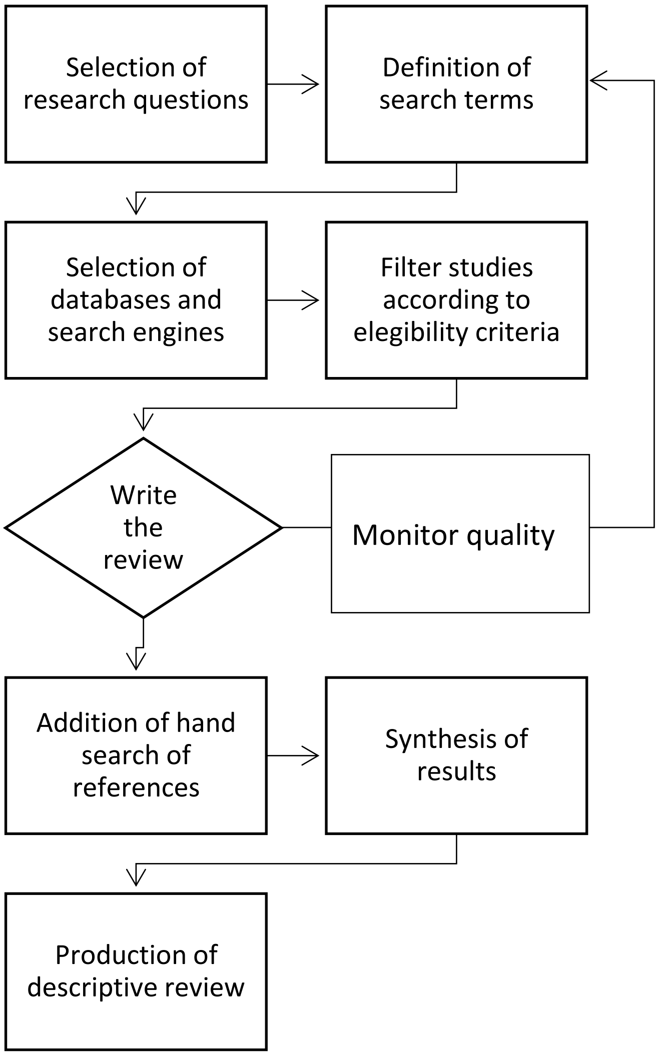


Figure 2.1. Steps in the literature review. Adapted from Fink (2013).

Following the definition of the search terms, an initial screening of publications was conducted on gold mining in Colombia for the period 2000 – 2017, using Scopus, Google Scholar and Web of Knowledge. Subsequently, the abstracts and full texts of the studies were assessed and classified according to the main topic addressed. The period 2000 – 2017 was selected because during this period the global production had increased to meet the rising demand for gold, paralleled by an increase in the price of gold, which has stimulated new gold mining activities around the world and made it feasible to mine for gold in areas that were previously not profitable for mining (Alvarez-Berrios and Aide, 2015). For information from government agencies and private organizations, a search was performed individually for each specific topic. In addition, relevant books on the topic were searched and finally, experts on gold mining in Colombia were contacted to gather additional information on specific topics that were not sufficiently addressed by scientific literature or reports. Given that gold mining in Colombia is a broad field, the selection of the literature for this review was performed based on the eligibility criteria suggested by Liberati et al. (2009). The following criteria were used:

- Type of studies: Selected literature must be related to gold mining activities in Colombia regarding environmental, social and economic impacts. We define gold mining as stated by the National Mining Agency of Colombia as “Science, techniques and activities related with the discovery and exploitation of mineral deposits, including open-pit mining, quarries, alluvial dredging, combined operations that include underground or surface treatment and transformation” (Ministerio de Minas y Energia, 2003).
- Topic: The selected literature should contain the words “gold”, “mining” in the title and/or abstract. “Colombia” should be mentioned at least once in the body of the paper; however, when referring to global aspects this term was removed from the search.
- Study design: Scientific literature, reports and regulations were eligible for inclusion in the review, as some subjects were related to specific organizations, government agencies or gold mining companies that may not have scientific publications.
- Year of publication: Literature published from 2000 – 2017 was retrieved.
- Language: English and Spanish literature were selected for this purpose.
- Publication status: For scientific literature, only international peer-reviewed journal articles and books from recognized publishers in the field of gold mining were selected. Reports and official documents were accessed directly at the webpage of the author organizations or government agencies and third-party webpage links avoided.

The results of the search were synthesized descriptively by means of interpretations of findings based on the experience of the reviewers, the quantity and the content of the literature. The quality of the review was monitored by comparing the constructs with other research from within and outside of the field. The review was also presented to other researchers and practitioners for comments.

2.3 Environmental perspective

2.3.1 Environmental challenges

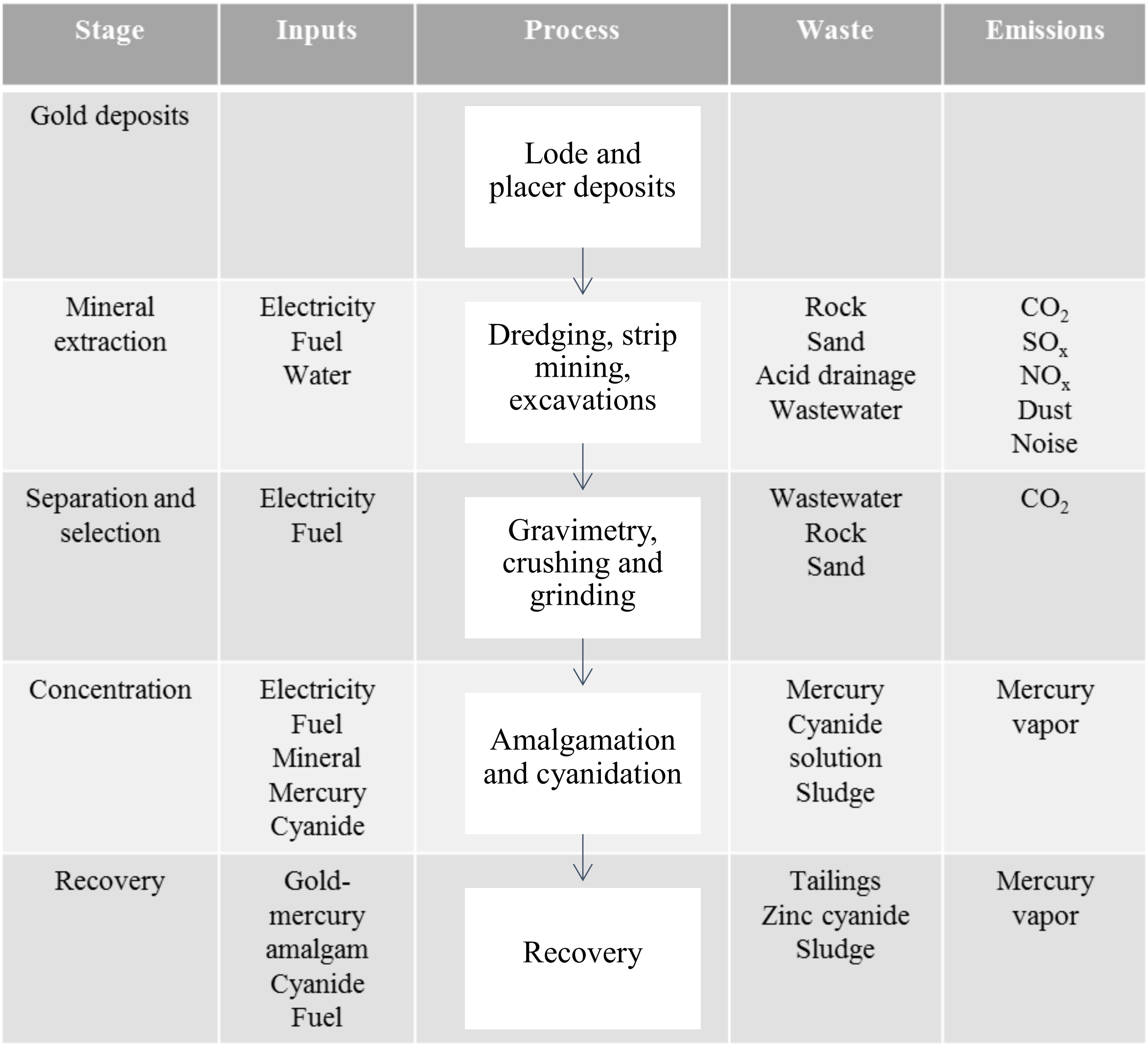
Waste generation and formation of technogenic surfaces

Given that gold is ranked as one of the best-performing assets globally, gold demand increased by 21% in the first quarter of 2016, showing the highest performance in almost three decades. In spite of a long-term decline in the demand for gold for technological devices and jewelry, the investment sector continues to drive the rising gold demand (World Gold Council, 2016). In 2015, Colombia ranked 18 among the gold-producing countries with an increasing trend over the previous 10 years (15.6 tons in 2006 and 59.2 tons in 2015)(World Gold Council, 2015). The increasing demand for the metal has led to more mining and greater waste production. The inflows and outflows of the gold extraction and recovery processes are illustrated in Figure 2.2. In 2015, the global gold production was 3,000 tons, with around 56,000 tons of global reserves in identified resources according to government and corporate reports (World Gold Council, 2016). Assuming that the average ore grade for gold is 2 ppm, then approximately 1,500 million tons of solid waste were generated in 2015 (USGS, 2016). The large volumes of excavated rocks and soil form waste deposits that cover the original soil and influence its ecological functions (Shlyakhov and Osipov, 2004).

The major types of waste deposits in Colombia have developed from dredged sediments that form dumps. Dredged sediment dumps consist of re-deposited sediments that have been washed by suction or bucket dredges. At the landscape scale, placer mining with suction dredges leads to modification of channels, beds and slopes in river valleys (Egidarev and Simonov, 2015). Mechanical dredging also destroys natural wetlands while at the same time creating man-made wetlands or flooded pits to supply water for the mining operations. The use of mechanical dredges is very common in north-eastern Antioquia, specifically in the Cauca and Nechi rivers. These operations have changed the hydrologic connectivity of the wetlands by partial or total dredging of these areas (Villa and Tobón, 2012).

According to the latest report published by the Colombian environmental authority in 2016, an area of 78,939 ha was affected by alluvial gold mining in 2014 (UNODC, 2016). Almost 80% of the gold mining areas are in the departments of Antioquia (33%) and Choco (46%). Around 8% of the total land of the country affected by dredged dumping sediments is concentrated in only one municipality, Nechi, Antioquia. According to UNODC (2016), 24,450 ha of natural forest and secondary vegetation were lost in 2014, mainly in Choco (77%). An analysis of the temporal degradation dynamics shows that between 2001 and 2014, an area of 44,746 ha was degraded by alluvial gold mining over the whole country (UNODC, 2016).

Mining of lode gold deposits also creates waste deposits, which are formed after the removal of the surface soil layer and underlying rocks. Moreover, pollutants can be released from the mining sites. Their type and magnitude depend on the mining technology, geology, topography and regional climate. For example, climatic conditions with high temperatures and humidity may stimulate reactivity of post-mining sites. Furthermore, physical rock transformations take place, such as the formation of coarse-grained material due to fragmentation. Chemical processes like oxidation, acidification, hydrolysis, metal leaching and precipitation of sulfates are other potential sources of pollution (Wahsha and Al-Rshaidat, 2014).



Stage	Inputs	Process	Waste	Emissions
Gold deposits		Lode and placer deposits		
Mineral extraction	Electricity Fuel Water	Dredging, strip mining, excavations	Rock Sand Acid drainage Wastewater	CO_2 SO_x NO_x Dust Noise
Separation and selection	Electricity Fuel	Gravimetry, crushing and grinding	Wastewater Rock Sand	CO_2
Concentration	Electricity Fuel Mineral Mercury Cyanide	Amalgamation and cyanidation	Mercury Cyanide solution Sludge	Mercury vapor
Recovery	Gold-mercury amalgam Cyanide Fuel	Recovery	Tailings Zinc cyanide Sludge	Mercury vapor

Figure 2.2. Inflows and outflows of gold extraction and recovery. (adapted from UPME, 2007).

Mercury emissions

Small-scale mining represents 20-30% of the global gold production (Veiga et al., 2014b) and 72% of the total gold production in Colombia (Calderon et al., 2016). Miners usually accumulate the ore and take it to processing centers known as '*entables*', where mercury is added to the whole high-grade material in small ball mills for the separation and extraction of the gold from the gold-bearing material. Generally, gold processing around the world occurs in rural districts or industrial zones, but in Colombia, the security risks for processing the extracted ore in rural areas are too high, and thus gold refiners set up their '*entables*' in urban centers (Siegel, 2013).

Mercury is preferred by miners because it is easy to use and transport, easily accessible and cheap, and allows them to perform the whole extraction process independently without having to rely on partnerships with other mining cooperatives or other miners (Güiza and Aristizabal, 2013). According to the Legiscomex database, in 2014 the most important providers of mercury to Colombia are, among others, Mexico (233.8 tons), Spain (184.6 tons), The Netherlands (180.3 tons), USA (152.1 tons), Germany (82.1 tons), and Peru (21.7 tons) (Ministerio de Minas y Energia and UPME, 2014). Tracking the fate of the imported mercury is complicated since it is mostly traded by private companies, but its use is generally attributed to gold mining (Ministerio de Minas y Energia and UPME, 2014).

Two techniques are used for gold amalgamation with mercury. The first technique uses all of the accumulated ore after crushing, grinding and washing. Then usually only 10% of the mercury adheres to the amalgam while 90% is immediately released. The second technique involves the gravimetric concentration of gold-bearing material where the heavier particles are collected in a pan and mercury is used to amalgamate the finest particles of the gold. In this process, 85-90% of the mercury adheres to the amalgam and the rest is released. After the amalgam is obtained (50% gold, 50% mercury), it is heated to recover the gold. When the heating process is performed outdoors, all of the mercury is released to the atmosphere, and if retorts are used to capture mercury vapor they can recover up to 95% reusable mercury (Güiza and Aristizabal, 2013). As means of payment, miners are usually asked to leave their tailings to be further leached with cyanide as residual gold to be sold by the '*entable*' owners (Saldarriaga-Isaza et al., 2013).

In 2011, Colombia was ranked as the world's third largest source of mercury emissions and as the world's highest per capita mercury polluter (Cordy et al., 2011).

Due to the lack of technologies to reduce mercury emissions, the metal is deposited in the sediments of nearby wetlands, which act as sinks and produce methylmercury, which is the most toxic mercury compound. Additionally, about 33% of the emitted mercury ends in solid waste, soil and water bodies (Marrugo-Negrete et al., 2015a). Studies that evidence the presence of mercury in different compartments of ecosystems in Colombia are listed in Table 2.2.

In northern Colombia, the Cauca and Magdalena rivers form a complex of wetlands rich in biodiversity but highly endangered by artisanal and small-scale gold mining. Pinedo-Hernandez et al. (2015) found concentrations of mercury of 0.196-1.187 µg/g in the sediments of the Mojana region, which is one of the regions most impacted by gold mining and also one of the most biodiverse regions of the world (Díaz, 2004). Considering that natural background levels of mercury in the region are 0.075 µg/g, the study proved that the Mojana is contaminated by substantial contributions of mercury from the Cauca River, which receives most of the tailings from the largest zone of gold exploitation in north-eastern Antioquia through flooding processes during the rainy season (Pinedo-Hernandez et al., 2015). Marrugo-Negrete et al. (2015b) studied the distribution of mercury sediments in two swamps of the Mojana region where the concentration in sediments ranged from 0.145-0.343 µg/g, whereas the elemental mercury fraction was 30% and the bio-available fraction 15% (Marrugo-Negrete et al., 2015b). These studies show that aquatic environments and human health are at risk due to the unstable mercury compounds that could enter water bodies and accumulate in the food chain.

A probabilistic risk assessment of inhalation of mercury-laden outdoor air conducted by Miguel et al. (2014) highlights the excessive levels of risk the residents of gold mining communities are exposed to. In addition, the fact that gold mining communities are generally fishing communities aggravates the risk (Miguel et al., 2014). Alvarez et al. (2012) found evidence of bio-accumulation of mercury and methylmercury in six fish species from the Nechi River, suggesting a high risk for frequent fish consumers given that an average of 56% of the mercury is present in the fish in its methylated form. The risk from ingestion of mercury-contaminated fish is compounded by the inhalation of mercury in the air. For miner smelters who burn the amalgam, the risk of developing adverse health effects is 200 times higher than the acceptable levels in most environmental standards (Miguel et al., 2014).

Table 2.2. Studies quantifying the accumulation of mercury in different environmental matrices associated with gold mining

Matrix	**Level of mercury (μg/g)**	**Location**	**Maximum mercury level (μg/g) permitted by WHO**	**Reference**
Tropical swamp	0.145-0.313	Grande Achi Swamp		Marrugo-Negrete et al., 2015b
River sediments	0.4-63.5	San Martin de Loba		Olivero-Verbel et al., 2015
Surface sediments	0.196-1.187	Mojana region		(Pinedo-Hernandez et al., 2015)
Fish	0.433-0.934*	La Miel and Nechi rivers	0.5*	Alvarez et al., 2012

*Mercury as methylmercury (Hg = MeHg / 1.0749)

Water, energy use and greenhouse emissions

Mudd (2007) presented a study on resource intensity based on data available for countries like Australia, Canada, South Africa and the United States in the context of a sustainability analysis of gold mining, and stated that the supply and consumption of economic energy is a key viability factor of gold mines, as well as the availability of a water supply. As with water and energy, greenhouse emissions through fossil fuels represent an environmental challenge for the mining industry globally, which is particularly problematic for gold mining that involves large-scale open-cut operations (Calvo et al., 2016).

Results of a recent life-cycle assessment show that the environmental footprint of gold production regarding greenhouse emissions, water consumption and solid waste burden is by several orders of magnitude greater than for the extraction processes of other metals such as Cu, Ni, Pb, Zn, Al or Fe (Norgate, 2012), which is attributable to the low concentration of gold in ores that causes emissions and high energy use in the mining and mineral processing stage.

To the best of our knowledge, not many mining companies have published sustainability reports that include information on water and energy use, and greenhouse emissions. Continental Gold reported a total discharge of 528,509 m^3 of water, related to domestic and industrial wastewater, groundwater inflow to an underground mine and water outflow from exploration tunnels. The internal energy consumption for 2015 was 3.0 gigajoule per ounce of gold produced. In addition, 3.9 gigajoules were consumed through non-renewable fuel and 21.5 gigajoules purchased for consumption (Continental Gold, 2015). Yet the company did not report on environmental performance regarding noise or air emissions. Mineros S.A. consumed 394,200 m^3/year of water and in terms of energy 3.58 gigajoule per ounce of gold produced (105,045,546 kW/h for 105,459 ounces of gold). In addition, it estimated that for alluvial operations in 2016, 0.64 tons of NOx were released, 9.7 $\mu g/m^3$ of PM10, and 0.14 $\mu g/m^3$ of SO_2. For underground operations, Mineros S.A. estimates that 18.6 $\mu g/m^3$ of PM10 were emitted (Mineros S.A., 2016a). The current technologies of extraction put considerable pressure on the environment. Therefore, to conduct further studies on the resource intensity of these operations, the mining companies need to publish their sustainability data, so that strategies can be designed to improve resource management and identify local and country trends.

2.3.2 Initiatives for environmental protection

Reclamation of waste deposits

Reclamation is the process by which waste deposits are returned to productivity, essentially by the re-establishment of a vegetation cover. The sustainability of the reclamation practices depends not only on vegetation redevelopment but also on the improvement of soil organic matter quantity and quality, restoration of nutrient cycling processes (Banning et al., 2008), soil stabilization, pollution control, and reduction of other threats to the environment (Sheoran et al., 2010).

After the deposit of the river sediments (gravel and sand), heavy machinery is used to grade the surface, and this can cause soil compaction (Meuser, 2013). Therefore, adequate re-contouring of the landscape to enable sufficient water infiltration and to limit runoff is necessary, thereby preventing soil erosion; the slope gradient should not exceed 1.5%. The geological origin of the deposited material that the waste deposit consists of is crucial for determining the reclamation opportunities of the terrain. For example, in the case of material stemming from the tertiary period, which is consequently sandy and contains pyrite, silviculture would be a suitable reclamation strategy, whereas deposits of alluvial sediments consisting of silt loams, loams, and silty clay loams are preferred for agricultural use (Meuser, 2013).

In Colombia, Thomas (2014) documents the existence of forest restoration projects that could become a model for reclaiming mined lands around the world. The author refers to the reforestation of 1,290 ha in Cáceres, Antioquia, that started in 2002 with *Acacia mangium* Willd. (Fabaceae) and some native tree species. To begin with, the barren landscape was reshaped using a bulldozer and the soil amended with sewage sludge, microorganisms, and nutrients. After ten years, *A. mangium* was replaced with native species to increase diversity. In this process, the local people were involved in the reclamation process and the social benefits in the form of timber sales and carbon credits were shared among them (Thomas, 2014). In another important gold mining region of Colombia, close to the municipality of Condoto in Choco, *A. mangium* and *Bixa orellana* L. (Bixaceae) were established on waste deposits created by small-scale mining activities (Mosquera et al., 2008). Both species were able to adapt to the conditions of the soil, with an average monthly stem growth of 0.2 cm without fertilization or amendments (Mosquera et al., 2008). Establishing an *A. mangium* plantation on a waste deposit resulting from small-scale mining in north-eastern Antioquia yielded high amounts of litter, which is an important source of organic matter and nutrients (Castellanos and Leon, 2010). The trees showed high foliar concentrations of nitrogen as well as a high capacity to associate with nitrogen-fixing soil bacteria, while phosphorus was the nutrient that limited the productivity of *A. mangium* most (Castellanos and Leon, 2010).

Along the same lines, the Colombian company Mineros S.A. has been establishing agroforestry parcels since 2000 to reclaim waste deposits in the municipalities of Nechi and El Bagre, Antioquia. The aim is to preserve native flora and fauna while supporting settlers and their families through the establishment of crops. The company provides the families with basic sanitation facilities and trains them to produce compost and establish nurseries with plant species selected for the reclamation process (Mineros S.A., 2016b). It considers agroforestry and the dual-purpose use of crops and livestock as an alternative to protective reforestation plantations. In addition to such reclamation practices, miners in north-eastern Antioquia are attempting to restore wetlands impacted by mechanical dredging through the establishment of native shrubs and tree species such as *Prioria copaifera* Griseb. (Leguminosae)*, Senna bacillaris* (L. f.) Irwin & Barneby*,* and *Pterocarpus* spp. (both Fabaceae). However, since seedlings often die because of droughts and/or flooding, it is important to consider hydrological balances in the planning stages of such wetland reclamation plans (Villa and Tobón, 2012).

Achieving reclamation of a post-mining site is a long-term process, and to improve such management strategies it is necessary to correctly interpret early signs of reclamation success or failure (Gould, 2012). Therefore, temporal trends in various indicators have been studied, such as changes in soil physical (Kuráž et al., 2012) and chemical properties (Abakumov et al., 2013; Banning et al., 2008), landscape functionality (Antwi et al., 2014; Gould, 2012), soil functional diversity (Lewis et al., 2010), carbon sequestration (Karu et al., 2009) and composition of soil bacterial communities (Li et al., 2014). In addition to the implementation of a reclamation strategy, the monitoring of specific recovery indicators is crucial. If negative trends are detected in a timely manner, problems can be fixed at low cost (Hendrychova, 2008).

For gold mining, it is necessary to perform long-term monitoring along with a runoff management plan to reduce acid mine drainage. For instance, covering potential acid forming material with non-acid forming material and a layer of clay can minimize the potential for water or oxygen to ingress within the site and considerably reduce the overall load of mine acid drainage (Changul et al., 2010).

Although the biophysical aspects of reclamation are highly relevant, there is a clear necessity to design and implement reclamation programs that engage local communities and consider the site-specific socioeconomic context (Chabay et al., 2015). An extensive body of research demonstrates that long-lasting reclamation projects rely not only on the suite of scientific practices and field observations to be performed but also on the support by local communities, effective policies, financing and appropriate legislation (Higgs, 2005).

Mercury reduction and remediation

Saldarriaga-Isaza et al. (2013) found that, in addition to the low cost of the mercury, two main factors explain its massive consumption in artisanal gold mining, i.e. low level of education of the miners and lack of credit facilities. Very often young children work in the mines instead of attending school. Lack of credit facilities, little savings of households, and skeptical attitudes toward alternative technologies are major barriers to the adoption of alternatives to mercury use. However, to sustainably reduce mercury pollution, it is pivotal to identify the needs and constraints of the miners, understand how they are organized, and find ways to address these issues (Veiga et al., 2014a).

After 2010, when the municipalities of Segovia, Zaragoza, Remedios, El Bagre, and Nechi in Antioquia were considered the world's largest mercury polluters through artisanal gold mining, the United Nations Industrial Development Organization (UNIDO), together with the regional government of Antioquia and several Colombian universities started the Colombia Mercury Project, which is aimed at reducing mercury use and losses (UNIDO, 2012). In spite of initial resistance, 39 mercury-free processing plants were constructed by 2013, and miners, as well as owners of "entables", were taught cleaner processing methods resulting in a 63% reduction in mercury entering the environment (García et al., 2015). This translates into a reduction of 46-70 tons of mercury used and released in Antioquia. Concurrently, airborne mercury concentrations were substantially reduced, e.g. in Segovia by up to 80%, mainly because of retorts, a decrease in milling speeds, and the use of mercury-free gold extraction techniques. In addition, a new regulation was established in which processing centers were restricted to non-urban areas (Cordy et al., 2015).

Other measures that helped to address mercury pollution were the enforcement of the law that prohibits the use of mercury in gold mining, the increase in the price of mercury, and contract agreements established between artisanal miners and gold mining companies operating in the region. The latter allows the miners to sell the extracted ores to the company to be processed by cyanidation without mercury as an alternative to bringing the ores to the "*entables*" (Saldarriaga-Isaza et al., 2015). These authors also suggest that a complementary form of intervention could be the creation of local associations among artisanal and small-scale gold miners, who would not only improve the relationship with the state but would also allow miners to accumulate the financial capital to acquire cleaner and more productive technologies.

Therefore, the authors explored the role of two institutional arrangements on associative entrepreneurship through an experiment with small-scale miners from Segovia and Remedios (Antioquia). Their findings suggest that a co-management scheme could encourage a well-established association of miners to access better, cleaner and more productive technologies.

However, beyond reducing the use of mercury in artisanal gold mining, other strategies to remediate the mercury pollution in soil and water are needed. Although physicochemical treatments can remediate metal-contaminated soils, they are usually expensive and can affect soil properties to such an extent that the soils can become unsuitable for plant growth (Marrugo-Negrete et al., 2015a). Therefore, phytoremediation is an alternative for remediation of mercury-contaminated soil. Phytoremediation of heavy metals is usually conducted with hyperaccumulator species, which have the ability to concentrate such metals up to 0.01% of their dry weight (Lasat, 2002). Marrugo-Negrete et al. (2016) conducted greenhouse experiments with *Jatropha curcas* L. (Euphorbiaceae) growing on mercury-contaminated soil that originated from the El Alacran gold mine in northern Colombia. It was found in gold mining areas where amalgamation processes are conducted with mercury, and where the soil is highly polluted with heavy metals. *Jatropha curcas* proved to be very suitable for the phytoremediation of mercury-contaminated soil given that it did not exhibit signs of toxicity, and the translocation of mercury to the aerial parts of the plant was very low, indicating that the mercury remained primarily in the roots (Marrugo-Negrete et al., 2016). Subsequently, the authors also tested *Thalia geniculata* L. (Marantaceae)*, Piper marginatum* Jacq. (Piperaceae) and *Cyperus ferax* Rich. (Cyperaceae), and all three-plant species proved to have the ability to accumulate high levels of mercury in their roots and shoots. However, due to the high heavy metal concentrations of plants used for phytoremediation, its use for feed or food could pose some risk to livestock, wildlife and humans (Marrugo-Negrete et al., 2016).

2.3.3 Opportunities for environmentally sustainable gold mining

Even though the association of mining with sustainability might be counterintuitive in the sense that the life of a mining project is limited by orebody geology and depends on market fluctuations, it is usually followed by lasting local economic, social and environmental effects. For this reason, the mining sector should look for ways to reduce local costs and risks to provide more positive and durable local benefits (Gibson, 2006). In the context of developing countries, Kumah (2006) provides a definition of sustainable gold mining as the one that "meets the needs of present and future generations, and internalizes the cost of adverse biophysical, economic, and social effects on a community". However, sustainability of a non-renewable resource must consider the fact that until the world demand for primary materials subsides, and recycling and reuse are the norm, the mining sector has a clear task: to make mining even more sustainable. For this purpose, global alliances have been formed, such as the Global Mining Initiative and the International Council on Mining and Metals. These organizations ensure that mining is conducted in such a way that is responsive to global needs and challenges (Batterham, 2017).

Sustainable use of resources

Efficiency in the use of resources is an important aspect in terms of reducing the impact on ecosystems and emissions resulting from mining activities (Ranängen and Lindman, 2017). So far, the information on water and energy use is limited to that provided by two mining companies. Therefore, it is an area with great potential for improvement. Energy and water use efficiency programs need to be implemented to promote sustainable use of resources. The gold mining sector should also encourage the use of solar energy, geothermal energy, hydroelectric, wind power and biomass (Awuah-Offei, 2016). In the specific case of the gold mining sector in Colombia with its rapidly expanding industrial infrastructure, the country has a good opportunity to increase competitiveness by applying energy-efficient best practices, as integrating energy efficiency into the initial design is typically less expensive and allows better overall results than retrofitting existing industrial facilities (McKane, 2010). In addition, the companies should reduce the use of water in the operations and stimulate water conservation as far as possible (Ranängen and Lindman, 2017).

The release of pollutants such as lead, mercury, cyanide, as well as the greenhouse gas emissions and any other substance that can have a detrimental impact on the environment and health should be regulated by comprehensive environmental legislation, especially for gold mining activities, which can pollute water bodies through direct intentional or accidental discharges and the soil through the generation of waste and pollutants discharge. For this purpose, the adoption of international standards for environmental protection could enhance environmental performance and sustainability of the gold mining sector (Da Fonseca, 2015).

In the last years, the integration of biodiversity issues into corporate environmental management practices has gained attention. Given the current rate and irreversibility of biodiversity loss, it is considered to be one of the main environmental challenges, especially in the case of natural resource-based organizations such as the mining industry (Boiral and Heras-Saizarbitoria, 2017). The daily operations of the gold mining sector have a direct impact on biodiversity, especially when they are in biologically sensitive areas in which various species have their natural habitats. For example, gold mining companies have named a mountain chain within the Colombian department of Santander as one of the largest untapped gold reserves in the world. However, NGOs and citizens are concerned about the prospect of a large-scale mining operation in the water-rich area of the *Páramo de Santurbán*, which includes 11,700 ha of land in which no economic activity is permitted (Ochoa, 2017). In Colombia, the *páramos* (Andean highland wetlands) are strategic territories that stimulate agricultural production systems and biodiversity conservation practices and are the main water supply for many urban centers (Duarte-Abadía and Boelens, 2016).

Therefore, biodiversity protection needs governmental intervention. Any development of the gold mining industry must be subject to legal requirements specific to biodiversity conservation, such as impact studies, rehabilitation operations and protection of threatened species. In addition, corporations should comply with voluntary agreements on biodiversity with government agencies, NGOs, policies and guidelines, as they take root at the local level, imply positive outcomes for stakeholders, and increase social acceptability of mining operations (Boiral and Heras-Saizarbitoria, 2017).

Development of a framework for sustainability assessments

The mining industry has economic, social and environmental impacts on society, therefore the criteria that need to be given priority depending on the location of the mining operations (Ranängen and Lindman, 2017). Local-level sustainability for the mining sector should be reflected as the continuity of the added-value and wealth generated from the exploitation of mineral reserves (Yaylacı and Düzgün, 2017). Therefore, given the uniqueness of every mining project in terms of technical characteristics, and environmental, social and economic impacts, it is necessary to develop a general framework for sustainability assessment that can capture the unique conditions of each mining project. The lack of concrete sustainability principles to assess the impacts of mining on community development can limit the understanding of the true effects of mining, which also limits the creation of development initiatives that might be more fruitful for the mining communities (Antwi et al., 2017).

Unsupported decision making as often occurs in gold mining projects, are usually problematic in terms of the influence of political and economic agendas, as well as the lack of capacity of the decision making. Therefore, the use of computer-based methods for risk and decision analysis can be implemented to evaluate and analyze scenarios considering environmental, social, economic and cultural criteria in the assessment (Mihai et al., 2015). Therefore, several frameworks for assessment of sustainability in mining have been developed worldwide. One of the most popular ones is the Global Reporting Initiative (GRI, 2017), which is based on indicators and has specific contents for the mining and extractive sector. Furthermore, there are several initiatives, such as the one lead by the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) that developed a policy framework that promotes the contribution of mining, minerals and metals sector to sustainable development and poverty reduction in more than 60 countries (IGF, 2013). Towards Sustainable Mining (TSM) is backed by a suite of protocols that mining companies measure and report in the areas of community outreach, energy and emissions, tailings, biodiversity conservation, safety and health, crisis management, and preventing child and forced labor (The Mining Association of Canada, 2017). The Leading Practice Sustainable Development Program for the Mining Industry (LPSDP) is a program that promotes sustainable development and industry self-regulation through a proactive adoption of practical principles on airborne contaminants, community engagement and development, energy management, mine closure and rehabilitation, and indigenous communities (LPSDP, 2016). However, the adoption of a sustainability assessment framework in Colombia should be done with the active involvement of stakeholders to integrate the measured parameters in the decision-making processes. Furthermore, it is critical that the framework for sustainability assessment should consider the entire life of the mine, from exploration to closure of a fully rehabilitated site. Maintaining continuity and coherence throughout the phases of temporary closure, waste management and rehabilitation should have a full consideration of long-term impacts and potential environmental legacies (Lèbre et al., 2017). Moreover, ecological footprint analyses of gold mining can be used as an indicator to monitor and regulate operations, quantify environmental impacts of mining, and promote long-term environmental sustainability. The ecological footprint is defined as the area of ecologically productive land such as cropland, pasture and forests that would be required to provide all the resources consumed and absorb the wastes discharged by a mining operation (Sinha et al., 2017). Sustainability of small-scale mining can be approached by providing technical knowledge on geological exploration, mineral processing and more efficient equipment. For this purpose, the necessary capital resources partnership agreements can be established with external investors, as it is likely that the owner of a small-scale mining facility does not possess the capital resources for engaging in sustainability improvements (Seccatore et al., 2014).

2.4 Social perspective

2.4.1 Social challenges

Poverty, illegality, and violence

As a consequence of the governmental support to mining activities, there has been a sharp increase in the number of licenses granted for gold mining between 2000 and 2012, but concurrently also a significant rise in illegal gold mining (Idrobo et al., 2014). The poor enforcement of property rights in the gold mining areas and an extremely low presence of the state in many areas of the country has led to the engagement of armed groups in gold mining. The increase in the international price of gold has had a considerable effect on the levels of violence as evidenced by the number of massacre victims (Idrobo et al., 2014). This can be explained by the fact that turf wars between illegal armed groups over municipalities they seek to control often leads to massacres and arbitrary homicides. Despite the high extent of violence, Idrobo et al. (2014) found that forced displacement did not increase in the illegal mining areas, probably because illegal mining is labor intensive, and displacing local inhabitants would lead to labor shortages and subsequently rising labor costs.

Evidence suggests that gold mining in Colombia is permeated by illegal groups linked to armed conflicts, criminality, and drug trade (Idrobo et al., 2014). In approximately 38% of the territory where alluvial gold mining is carried out, coca for cocaine extraction is also grown (Figure 2.3). In the departments of Putumayo, Nariño, and Caquetá, more than 80% of the territory is affected by both coca cultivation and alluvial gold mining. In the departments of Antioquia and Choco, on 30-35% of the area used for alluvial gold mining, coca plants are also grown (UNODC, 2016).

According to the Environmental Justice Atlas (Specht and Ros-Tonen, 2016), 36 out of 99 environmental conflicts in Colombia between 2012 and 2015 were related to gold mining. In addition, Colombia is the country with the highest number of environmental conflicts on the South American continent (UNODC, 2016). Moreover, the attention to drugs alone as a conflict source has overshadowed the degree to which illegal groups have permeated economic activities (Rettberg and Ortiz, 2016). For instance, in regions where anti-drug efforts have been successful, gold mining emerges as a substitute for illicit crops, often promoted by the Colombian government as a driver of development but concurrently pursued by criminal actors as an alternative source of income (Rettberg and Ortiz, 2016).

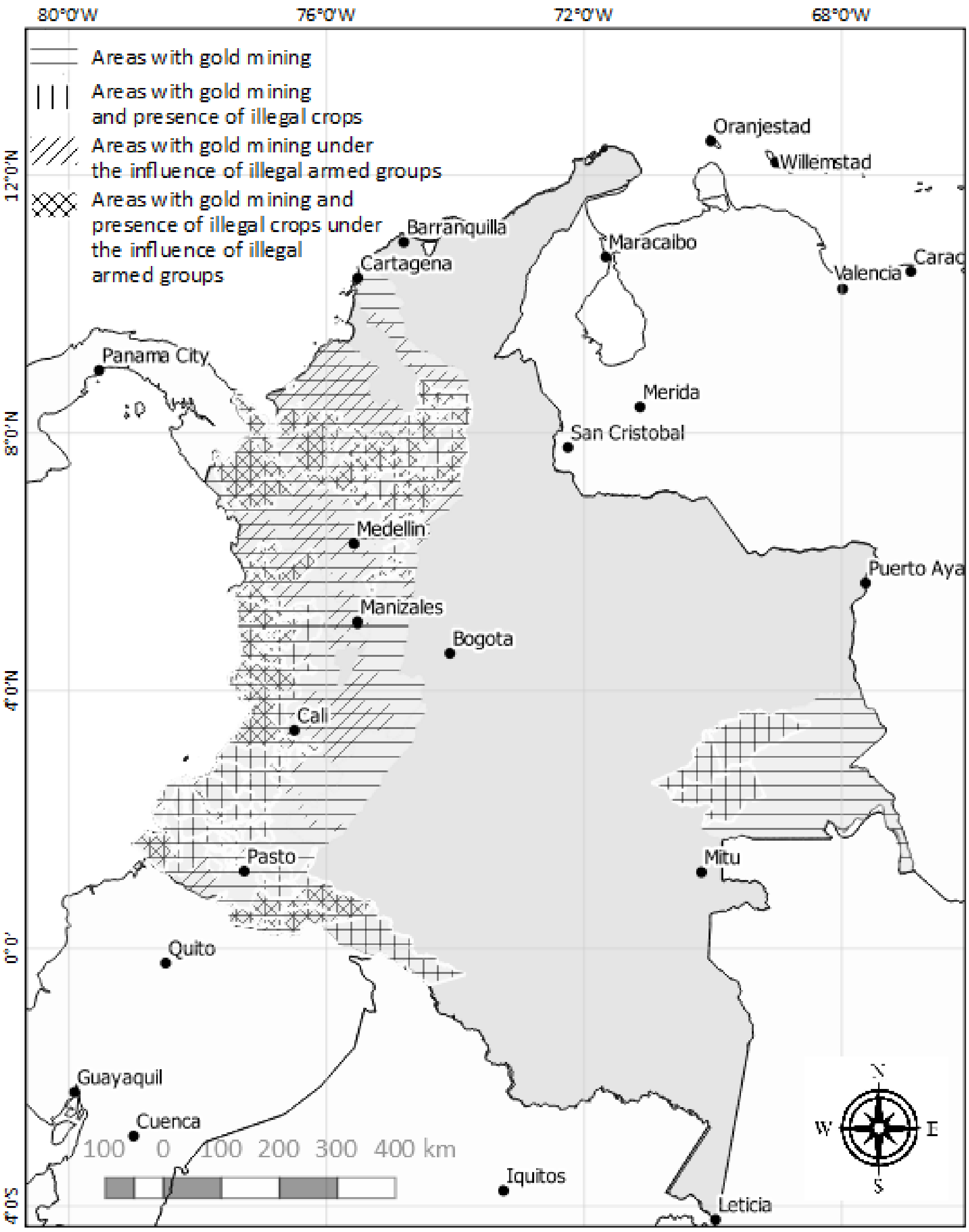


Figure 2.3. Gold mining linkage with illegal armed groups and production of illegal crops in Colombia. Horizontal lines represent the most important gold producing areas (UPME, 2016). Vertical lines rep represent municipalities with gold mining activities and presence of illegal crops (UNODC, 2017). Diagonal lines represent gold mining areas under the influence of illegal armed groups in 2017 (Indepaz, 2017). Crossed diagonal lines represent areas with gold mining activities and presence of illegal crops under the influence of illegal armed groups.

Tubb (2015) found a common behavior generating conflicts within the communities. To share the profits of an increased gold production, artisanal gold miners frequently rent their territory to small-scale miners who use excavators for exploitation. Therefore, small-scale miners often work where artisanal miners have already mined, and usually set up scattered mining camps and start to use large excavators and floating dredges. The scale of deforestation, erosion, sedimentation and mercury contamination is much larger when mining is performed by excavators than by artisanal miners. This behavior often generates conflicts with the adjacent communities because of the resulting deforestation, mercury contamination and higher malaria incidence due to the increased abundance of water-filled pits. For instance, between 2010 and 2013, in the Colombian gold mining districts of Bolivar, Choco, Nariño, and Antioquia 36% of the malaria cases were related to gold mining activities (Castellanos et al., 2016). Legal and illegal mining areas are generally located in regions with high prevalence of malaria, and the substantial migration induced by mining activities favors the circulation of the pathogens through movement of infected individuals throughout the mining districts (Castellanos et al., 2016).

Acemoglu et al. (2012) compared poverty rate and secondary school enrolment between gold mining municipalities in Colombia and those without gold mining and found that gold mining municipalities had almost 15% higher poverty rates and 10% lower secondary school enrolment rates. Child vaccination rates were 30% lower in gold mining municipalities than in the neighboring municipalities, the latter rates comparing well with those in the rest of the country. In addition, municipalities without gold mining had around 20% higher water and electricity supply coverage than the gold mining municipalities. Malaria prevalence was four times higher in gold mining municipalities compared with the average of the country, mainly because of higher rainfall, generally warmer climates and more widespread water pools in the mining regions. All these disadvantages are further aggravated by the low degree of state presence in the gold-deposit areas of Colombia (Acemoglu et al., 2012).

Moreover, gold producing municipalities, specifically in Antioquia, have substantially higher numbers of violent deaths, child mortality, unfulfilled basic needs and greater misery than in the rest of Colombia (Rudas, 2013 and Table 2.3). This means that gold mining does not represent significant improvements in the living conditions of the population. The promotion of FDI in large-scale mining projects by the Colombian government has additionally raised fears in small-scale mining communities that the state plans to clear away their business in favor of multinationals. Therefore, civil groups are increasingly monitoring conflicts between mining companies and such communities (Tubb, 2015).

The reliance of the Colombian government on large-scale mining projects has been questioned, especially the expectations that this would improve the living conditions of affected communities. Rudas (2013) analyzed social indicators in municipalities in Antioquia where a large mining company operates (Table 2.3), and showed that violent deaths and child mortality were not different compared to other gold mining municipalities of the region. The levels of unfulfilled basic needs and the proportion of the population living in extreme poverty were considerably higher than in the rest of the gold mining municipalities of the department. Thus, it appears that formalized large-scale mining does not automatically lead to an improvement in the living conditions of the people in such regions.

According to the Colombian government, small-scale and artisanal mining is often performed in a “traditional manner, lacking appropriate technology and characterized mostly by the informality and subsistence, which makes it unsafe, non-profitable, uncompetitive and environmentally not sustainable” (Urán, 2013). Repeatedly, literature as well as legislation groups the artisanal and small-scale mining sectors together, and contrasts them with the formal large-scale mining sector that usually can count on support by the state (Tubb, 2015).

Table 2.3. Social indicators of gold mining regions compared with non-gold mining municipalities of Antioquia, Colombia (based on Rudas, 2013)

Indicator	**In gold mining municipalities**	**In non-gold mining municipalities**	**In municipalities where a large mining company operates**	**In the other gold mining municipalities**
Violent deaths (per 100,000 inhabitants)	96	47	81	98
Child deaths (per 1,000 births)	28	25	30	28
Unfulfilled basic necessities (%)	48	35	61	46
Population living in misery (%)	22	13	35	21

Informality of miners

Despite the regulations on artisanal mining in Colombia, informality remains strong. Informality here refers to any mining activity that is performed without a license from the official Colombian Environmental and Mining Authority. Informal mining triggers informality in many other dimensions like contract agreements without guarantee of social security, lack of environmental management plans, and unaccomplished safety regulations within the mines. In addition, it disrupts the tax regulations by evading the payment of royalties to the state (Chen and Perry, 2014).

In 2011, according to the most recent mining census of the Ministry of Mines and Energy, 86.7% of the gold mining production units (i.e. six or more miners) did not possess a mining license, and only 1.5% of the mining production units adhered to an environmental management or restoration plan (Ministerio de Minas y Energia, 2011). Approximately 15,000 to 30,000 artisanal gold miners in Antioquia perform their activities informally in the Lower Cauca River and the north-east of the department. The majority of Antioquia's gold production stems from five municipalities, i.e. Segovia, Remedios, Zaragoza, El Bagre and Nechi with a total population of 162,000 inhabitants (García et al., 2015) that contribute almost 30% to the national gold production (SIMCO, 2017). Given the precarious conditions, informal mining affects the welfare of the population, causes significant environmental impacts, and threatens biological resources (Goñi et al., 2014).

Post-conflict considerations for gold mining activities

In some of the territories in which the peace agreement is primarily going to be implemented, some extractive processes are taking place, where armed illegal forces have a strong influence keeping the mining activities under surveillance, charging fees for the transit of machinery, designating boundaries, etc. Therefore, it is important to acknowledge that implementing the peace agreement in these areas might generate a greater environmental impact as it might leave unfilled spaces that can later be taken over by new armed forces. Furthermore, the deactivation of these coercive structures might allow the entry of mining companies or interested parties that are willing to develop extractive activities that are not feasible due to the armed conflicts (Aponte et al., 2016). This could mean that the benefits through the peace agreement might be overshadowed by the increase in environmental degradation. McNeish (2017) considers that rather than forming the basis for the equitable development of the country, an expansion of the extractive sector can fuel the mutation of the armed conflict and result in a series of humanitarian crises throughout the country that already has the largest internally displaced population in the world.

The challenge concerns the question of how to involve armed actors in conflict resolution when they have the apparent purpose of attracting economic resources. The question then arises as to whether the state should guarantee the common interests of the other parties in the conflict and ensure the protection of the rights of the citizens (Valencia and Riaño, 2017). Therefore, it is important to consider the presence of armed actors in the dialogue and joint construction of the territory. However, the need to involve them in these scenarios should be viewed with caution, because armed groups constitute a threat to the communities. The decision must be taken after investigating the role of the armed groups with different parties in the framework of an ethnographic study that allows identifying information sources (Valencia and Riaño, 2017).

2.4.2 Initiatives for improvement of community well-being

Community involvement

The mining industry impacts not only the environment but also local economies, social structures and cultural values (Lyytimäki and Peltonen, 2016). Communities that directly depend on natural resources and environmental services for their livelihoods are the most affected. Such communities often experience displacement by mining activities and suffer from the effects of the creation of wastelands from open-pit mines and topsoil removal, pollution of water systems, air and soil, acid leaching and deforestation (UNDP, 2012). According to Schueler et al. (2011), surface mining of gold has weakening effects on regional development. For instance, local people experience that the foundations of their livelihoods erode, that they lose income opportunities, suffer from health problems and social and cultural alienation, as well as from conflicts over the use of land, as farmers are often forcefully evicted from their farmland (Schueler et al., 2011).

To reinstate the livelihood of affected farmers, the reclamation of gold-mining spoils can be performed through a combination of woody perennials, annual crops and livestock that can contribute to soil improvement in terms of structure, organic carbon, and nutrient status while concurrently producing time savings, fruit, timber, and fuelwood for the community (Hermawan, 2016). Communities should be actively involved in such reclamation processes, e.g. through weed and fire control, the supply of local seeds, seedling establishment, and maintenance of trial farms, while the risks of crop establishment and grazing should be assessed according to biophysical characteristics of the site that might influence land productivity and grazing activity (Tetteh et al., 2015a).

Moreover, risk factors that might influence farmers' and cattle grazers' ability and willingness to comply with the reclamation-related caveats of land management need to be addressed. Farmers should be engaged from the early stages of reclamation planning to increase their commitment to voluntarily comply with the challenges of reclaiming mined land (Maczkowiack et al., 2012). In a case study of land reclamation by AngloGold Ashanti Ltd., 90% of the community was involved (Tetteh et al., 2015a). Their perceived main benefits were improving food security by raising agricultural production, opportunities for marginalized groups to access land, increase in the monetary value of land, mitigation of environmental hazards, creation of employment, prevention of conflicts, and enhancement of peace and stability.

In addition to reclamation schemes that engage communities, initiatives like Oro Verde have emerged from the communities to address their own needs. Oro Verde began when artisanal miners looked for support beyond the public administration and established links with non-governmental organizations (NGOs) that were active in the Choco region. Since 2000, the Oro Verde initiative has developed certified responsible mining practices, propelling a fair-trade movement around responsible small-scale mining. Gold is extracted by artisanal miners who comply with strict ecological standards and these products are sold under the Oro Verde brand name to fair-trade markets in Europe and North America (SEED Awards, 2009). The result was a new governance system in which local regulations and national laws and policies were applied such that the miners were officially recognized by Fairtrade-Fairmined, an international NGO operating in Colombia. This achievement has led to national and international recognition as well as economic benefits, as the miners can sell their product at prices up to 15% higher than the normal market price (Sarmiento et al., 2013).

A joint initiative created by the Colombian Ministry of Mines, the Antioquia Secretary of Mines, artisanal and small-scale miners, and AngloGold Ashanti Ltd. triggered the creation of a government-led model of coexistence. Under this approach, a separate legal entity subject to environmental compliance and regulations was created for the miners. The miners are provided with tools and resources to work safely in designated areas with good artisanal mining potential (AngloGold Ashanti, 2015).

Corporate social responsibility

In the context of the mining sector, corporate social responsibility implies compensating the disadvantages for current and future generations caused by depletion of a non-renewable resource. This compensation is understood as an investment in human and social capital to reflect the expectations of the community (Calderon et al., 2016). Yet community members in gold mining regions often perceive that corporate social responsibility agendas are utilized as a means for gaining social acceptance to operate rather than for pursuing adequate compensation schemes for communities affected by the mining activities. This might be attributable to the often-limited community engagement by the mining companies. Also, the presence of armed conflicts in gold mining regions can hinder mining companies from engaging with the communities (Buitrago and Ali, 2016).

In addition, gold mining in Colombia also takes place in precious ecosystems like the 95,000 ha Santurban Moorland, one of the areas rich in both flora and fauna and acting as headwaters for the whole country. About 60,000 ha of the moorland contain gold deposits susceptible to exploitation. Several mining companies are operating in the area following only minimum standards for the application of corporate social responsibility and with little evidence of the use of cleaner production methods or mitigation efforts (Morales Méndez and Rodríguez, 2016).

Health interventions are additionally important elements of corporate social responsibility. In Antioquia, Mineros S.A. focuses on vector control programs for malaria, and provides (limited) treatment for diseases like diabetes, obesity, and gum disease, and additionally provides eyesight tests and audiometry to both community members and employees. Moreover, mine workers are sensitized by programs that include awareness and education on alcoholism, drug addiction and smoking to prevent both diseases and accidents on the mining sites (Calderon et al., 2016).

However, corporate social responsibility should go beyond compensation and reclamation, as companies are also responsible for monitoring possible health consequences of communities living in such reclaimed areas. For example, AngloGold Ashanti Ltd. defines successful reclamation as the ability to support plant growth and maximize land productivity without heavy metal accumulation exceeding well-established safety thresholds (Tetteh et al., 2015b). In contrast, Tetteh et al. (2015b) found heavy metal concentrations in crops grown on waste deposits resulting from previous mining activities of AngloGold Ashanti Ltd. to be considerably above the recommended threshold levels even 11 years after reclamation.

2.4.3 Opportunities for a socially sound gold mining

Royalty distribution

Prior to 2011, the constitution stated that 80% of the royalty proceeds had to go to provincial governments in gold producing regions, and the remaining 20% of the National Royalty funds. After the constitutional refund, direct royalties to producing regions were reduced to 20% and created regional royalty funds for the remaining 80% aimed to finance regional development and infrastructure projects (Bonet et al., 2014). The current system of distribution and allocation of royalties in Colombia has sought to overcome the waste of resources derived from extractive activities. However, this scheme has generated an unexpected effect in the municipalities affecting the dynamics of the sector's activity.

With the national management of the royalties and the lower payment of direct royalties to the municipalities, any incentive that a local government must promote and support extractive ventures has been eliminated. The mayors and governors are left without the royalties, but in their territories, they suffer from conflicts generated by the mining industry (Valencia and Riaño, 2017). With this scheme, ensuring that the local institutions are committed to the development of a sustainable extractive sector that contributes to the local communities is a real challenge. Therefore, the government must find a middle ground for the allocation of royalties so that the loss of farmland area and forest benefits, and the decrease in agricultural yields can be compensated to the communities in mining areas.

Corporate social responsibility

The definitions of Corporate Social Responsibility (CSR) contain five key dimensions: social, environmental, economic, voluntary and stakeholder. However, in the last years, industry frameworks for CSR have been more closely aligned with the principles of sustainable development. This implies that the companies are supposed to gain a Social License to Operate (SLO), which goes beyond the legislation requirements and involves the understanding of the needs and interests of the local community (Bice et al., 2017). In Colombia, the SLO is currently not a legal requirement for mining companies to operate. However, it should be part of the mining culture of the country, as it provides the legitimacy that is necessary when a society endorses the presence of a mining project in its surroundings as the first step to consolidate a win-win scheme between mining companies and communities, which can also be reflected in environmental protection (Agencia de Noticias UN, 2015).

Furthermore, incorporating community planning in the early stages of the mine life cycle can draw stakeholders into viable options and ensure that resources are used strategically, which is key for local communities involved in CSR (Fordham et al., 2017). A key aspiration for the development of gold mining in Colombia should be the creation of Enduring Community Value (ECV), which means to identify ways to convert financial capital from resource development into financial, natural, human, and built and social capital for the community (Davies et al., 2012). This is a highly salient concept in resource sector development that takes place in remote areas where communities have inherently faced significant development challenges, such as reduced government service delivery, pressure on agriculture due to globalization, and under-investment (Hogan and Young, 2014).

A range of CSR activities that can contribute towards ECV can be oriented towards compensation payments made to the communities for relinquishing their land rights for mining (Craik et al., 2017). This can be reflected in long-term investment for health, education, business development and employment programs. However, the capacity to generate ECV relies strongly on effective leadership within the communities. These programs are fundamentally important to ensure that the communities are directly benefitting from the financial flows generated by mining activities (Blackwell and Dollery, 2013). These initiatives can potentially have broad implications for developing sustainability solutions in the gold mining industry, especially for the rural communities as they are in need for more diverse sources of capital to boost community development (Fordham et al., 2017).

Conflict management

Research has found that the defense of livelihoods is the central claim in mining conflicts, as mining can jeopardize local livelihoods, which are usually dependent on agriculture, cattle, and forests. Beyond the defense of livelihoods, the community also aims to protect not only a source of subsistence and income but also its embedded meanings, values and identities (Walter and Urkidi, 2017). The fact that mining interests are privileged over agricultural land tenures together with the power of the mining industries to influence government decisions usually increases public concern (Duus, 2014). In 2017, there was open opposition by the communities of some rural areas in Colombia to gold mining exploration and exploitation by mining companies. For example, in the municipality of Cajamarca, 98% of the population (approx. 20,000 inhabitants) voted to ban mining in the municipality, especially the exploration work conducted by AngloGold Ashanti Ltd., which was considered as the potential largest gold mining project in Latin America. The inhabitants of Cajamarca claim to have made this decision to privilege the agricultural activities in the municipality. This decision came amid legal wrangling over environmental regulations and community opposition against government-granted mining permits (Cobb, 2017).

There are many factors underlying the conflicts in the gold mining sector, which often include artisanal and small-scale mining activities, ineffective engagement of local people, corruption, economic and environmental concerns, land use, and labor issues (Hodge, 2014). The right of affected communities to take part in high-impact decisions is recognized in a variety of norms and rights in Latin America, but also often neglected or incorrectly executed. Therefore, the creation of alternative participation mechanisms could help to prevent the worsening of social conflicts around large extractive projects. This need to approve and implement laws that regulate the right to prior consultation has been supported by recent rulings of the Constitutional Court in Colombia (Jahncke Benavente and Meza, 2010). Such consultations are usually promoted by social movements and supported by local governments and can be a strategic tool that reclaims the right of affected populations and indigenous people to participate in high-stakes decisions that affect their territories, livelihoods and future (Walter and Urkidi, 2017).

In addition to consultations, Hodge (2014) discusses that the key success factor for mining companies is the creation of relationships with host communities characterized by authenticity, respect, inclusiveness, and transparency. The creation of this type of relationship is not to be legislated but should evolve from the attitudes reflected in cultural sensitivity and action based on dialogue and collaboration. In the specific case of gold mining, large companies need to set up relationships not only with host communities but also with artisanal and small-scale miners for conflict prevention and management. In this context, the World Bank (2009) proposed a series of actions that large-scale mining companies can implement to manage the relationship with artisanal and small-scale mining communities. These actions consist of the promotion of a better legal and regulatory framework for the regularization and formalization of artisanal miners, as well as the designation of areas that can be shared between large- and small-scale mining activities. Furthermore, the mining companies can provide technical help to artisanal miners through capacity building programs aimed at improved productivity with better environmental practices. However, to execute these actions, under certain circumstances the government should take the lead by either arbitration or law enforcement.

Mining as a foundation for peace

As mentioned before, the Colombian government claims that the mining and energy sector is a key driver for development and economic growth. It is also seen as a vital source of state income to cover the costs of the peace agreement and continued economic development (McNeish, 2017). In this context, the vision proposed by the Group for the Dialog on Mining in Colombia (GDIAM) is based on three fundamental aspects: mining should be inclusive, resilient and competitive (GDIAM, 2015). GDIAM emphasizes that the state needs to guarantee the active participation of the communities in every phase of the mining process, i.e. exploration and exploitation. In addition, GDIAM considers that mining activities should be resilient in the sense that they should leave a net positive impact in the social, economic and ecological system, accounting for prevention, mitigation, restoration and compensation of immediate impacts. In addition to this, GDIAM emphasizes the fact that mining should be competitive, i.e. profitable in social, economic and environmental aspects.

To achieve this, Aponte et al. (2016) suggest that the first step should be a clear and precise classification of the types of mining performed in the country to differentiate artisanal and informal mining from illicit extraction, so that the first become formalized through promotion and protection alternatives, and the latter is controlled by the implementation of repressive strategies by means of the coercive apparatus of the state (Aponte et al., 2016). In addition, it is necessary to implement regulations on the demand of resources that are extracted in areas under the influence of illegal armed forces and that might finance these illegal groups, as is the case of the regulation initiative documented in the OECD Due Diligence Guidance for Minerals from Conflict-Affected and High-Risk Areas (OECD, 2011). This guide provides a framework for detailed due diligence as the basis for responsible global supply chain management of minerals, with one chapter dedicated to supplementing on gold. It focuses on steps that companies should take to avoid contributing to conflicts and abuse of human rights in supply chains of gold potentially sourced from conflict-affected areas. The first steps correspond to the establishment of strong company management systems to identify and assess risks in the supply chain to find potential sourcing of gold from conflict-affected areas. Echoing the necessity of an adequate classification of the miners, the guide, in particular, recognizes that artisanal and small-scale gold miners are encouraged to remain involved in the due diligence efforts of their customers and to engage in formalization processes in order to be able to maintain due diligence in the future (OECD, 2011).

2.5 Conclusions

The Colombian government envisages gold mining as an important driver of the development of the economy, although its expansion during the past decade has highlighted both its risks and benefits. From the environmental perspective, with the increase in gold mining, the land degraded by mining activities will significantly increase, as the past has shown that the area has almost doubled in the last 15 years. The increase in small-scale and artisanal gold mining activities can lead to more mercury emissions that will pollute natural ecosystems and pose a health threat to the communities living in gold mining areas. Furthermore, the current technologies used for industrial gold mining will continue to put pressure on the environment due to the high resource intensity of their operations.

From the social perspective, the increase in gold mining activities has triggered both legal and illegal exploitation of gold, leading to increased engagement of illegal armed groups in gold mining. Evidence also suggests that gold mining in Colombia is directly linked to armed conflicts, criminality, and drug trade. In gold mining communities, poverty rates, child mortality, violent deaths, and unfulfilled basic needs are higher than in those where no such activities take place. Despite many regulations, informality in gold mining still remains strong, which leads to an extractive activity being conducted without social security, environmental management or safety regulations, and the evasion of royalty payments to the state. Another issue to be considered is that the implementation of the peace agreement in areas where illegal armed forces have a strong influence may lead to increased environmental degradation, as the deactivation of coercive structures may allow informal extractive activities that were not feasible due to the armed conflict.

Despite these many drawbacks and the often negative image in the public, gold mining has the potential to confer economic benefits to some communities. Therefore, finding proper coping strategies for areas affected by gold mining is of utmost importance. Reclamation practices should be planned and managed under a scheme that includes soil stabilization with the use of heavy machinery, pollution control and landscape restoration. In addition, the use of toxic substances like mercury needs to be reduced by substitution with mercury-free processing plants, as well as through the creation of associations among small-scale and artisanal miners to both acquire cleaner technologies for gold processing and associate with mining corporations to process the extracted ore. In addition to the reduction of mercury consumption, adequate remediation strategies should be created for mercury-polluted wetlands, soil and rivers. To achieve this, a crucial step is to develop effective regulatory frameworks aimed to reduce informality of mining, provide guidelines for planning and designing environmental management plans, develop safety regulations for mining activities, and protect biodiversity hotspots that harbor potentially exploitable gold deposits.

To add social value to gold mining activities, the local communities ought to be engaged, and their needs and expectations considered. To this end, adequate compensation schemes for communities affected by mining activities need to be created. Furthermore, monitoring health consequences of mining activities for people living in surrounding areas is of outmost importance within the compensation schemes. Effective communication and transparency between the mining companies and the local communities will reduce conflicts and promote confidence as well as a deeper understanding of the communities to make decisions on post-mining use of the land and the design of reclamation schemes that help the community.

There is enormous potential for the gold mining sector and the affected communities to receive help from knowledge generated by scientific research. A knowledge gap still exists on life-cycle assessment of gold-mining processes at different scales in the country. In this regard, quantification of greenhouse emissions, water consumption and solid waste burden has not yet been systematically performed in the country, and represent a considerable opportunity for improvement of the sector. Despite the efforts performed by researchers and mining companies, little is known about forest restoration, biodiversity and ecosystem functioning of areas affected by gold mining waste. Hydrological studies need to be conducted to understand the dynamics of wetlands created by mechanical dredges in alluvial gold-mining areas, as well as the implications of changes in the course of the river due to this activity. Furthermore, it is necessary to develop a sustainability assessment framework that considers mining activities of a fully rehabilitated site from exploration to closure with the active involvement of stakeholders aimed to integrate the performed assessments into decision-making processes.

On the path to socially sound gold mining, the royalty distribution schemes need to be designed in such way that ensures the commitment of local institutions in the development of a sustainable gold mining sector that compensates the lessened livelihood opportunities of the community through efficient resource allocation. This compensation can also be achieved through the implementation of corporate social responsibility plans that contribute to maintaining community value by converting financial capital from resource development into natural, human-built and social capital for the community. Furthermore, the defense of community livelihoods is one of the central claims in mining conflicts, therefore alternative mechanisms of participation supported by the creation of relationships between mining companies and communities based on respect, inclusiveness and transparency could help to prevent the increase in social conflicts around large extractive projects.

Although these issues are not a complete list for a future research agenda, it is necessary to emphasize the need for establishing links between the scientific community, gold mining companies, government and affected communities to create the knowledge needed to manage and restore ecosystems degraded by gold mining activities.

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3. INTEGRATING LOCAL AND SCIENTIFIC KNOWLEDGE IN SOIL MANAGEMENT IN AREAS COVERED BY GOLD-MINING WASTE UNDERGOING RECLAMATION THROUGH AGROFORESTRY

Abstract

Alluvial gold mining generates a vast amount of deposits that cover the natural soil and negatively impacts riverbeds and valleys, causing loss of livelihood opportunities for farmers of these regions. In Colombia, more than 79,000 ha are affected by alluvial gold mining, therefore developing strategies to return this land to productivity is of crucial importance for the communities living in gold mining areas. A novel reclamation strategy has been created by a mining company, where the land is restored through the establishment of agroforestry systems in which agricultural crops and livestock are combined to complement reforestation in the area.

The purpose of this study is to capture the knowledge of farmers who perform agroforestry in areas with deposits created by alluvial gold mining activities. Semi-structured interviews were conducted with farmers with regard to soil fertility, management practices, soil heterogeneity, pest outbreaks and weeds. In order to compare the farmers' perception of soil fertility with respect to the physicochemical properties of the soils, the farmers were asked to identify spots within their farms that had exhibited both good and poor yields. Soil samples were collected in order to correlate farmers' perceptions with soil physicochemical properties.

The findings suggest that the main challenge that farmers face is the identification of fertile soil for crop establishment. They identify fertile soil through visually analyzing soil color and compaction as well as the use of spontaneous growth of specific plants as indicators of soil fertility. For less fertile areas, nitrogen-fixing plants are used as green manure to restore soil fertility.

3.1 Introduction

Local knowledge refers to the informal knowledge held by land managers involved in environmental decision making. Scientific knowledge refers to explicit knowledge derived from the application of formal methods to produce valid and reliable results (Reed et al., 2007). The complementary role of indigenous to scientific knowledge in agriculture relies on the fact that experimental research can be used to improve the information upon which farmers make decisions. However, it is questionable to rely only on scientific methods to fill the gaps about sustainable management of agroecosystems (Barrios and Trejo, 2003). A major challenge for researchers working on any topic of environmental management is the development of management options that are useful for land managers, and that consider local knowledge alongside scientific knowledge (Raymond et al., 2010). An objective of scientific research should be to stimulate a social learning process that combines knowledge from local stakeholders with scientific knowledge of researchers to develop management options that could help land managers to improve their productivity and prevent degradation of natural resources (Reed, 2008).

The key aspects that need to be addressed to attempt knowledge integration are capturing existing knowledge, engaging different types of knowledge, and applying a knowledge integration process (Raymond et al., 2010). A suitable strategy to capture the knowledge of land users is the use of qualitative interviews that can be subsequently synthesized to extract lessons regarding reclamation, management and research in a specific area (Botha et al., 2008). Participatory soil sampling is a tool that can be used to engage local and scientific soil knowledge through the integration of scientific and local soil quality indicators (Barrera-Bassols et al., 2009). Previous research has shown that cluster analysis of soil properties can reveal a strong correlation with the local perception of soil quality (Barrera-Bassols and Zinck, 2003). In addition to these aspects, other factors should also be considered such as the socioecological context of the system and the institutional structure for management including the strategies, ideas and skills of farmers (Cundill and Fabricius, 2009).

It is therefore suggested that to sustain agricultural productivity and restore areas covered by alluvial gold mining waste, local knowledge of the farmers and the knowledge derived from scientific research need to be integrated into a conceptual framework (Figure 3.1). Integrated knowledge generated from the assimilation of both farmer and scientific knowledge should be at the center of the decision-making process. The inputs for making decisions regarding a specific field or practice are: (i) the production objectives of the farmers that refer to the amount and quality of crops, trees and animals that the farmer needs to produce, (ii) ecological parameters such as climate, hydrology, weeds, inherent properties of the waste deposit, compaction, soil texture, and (iii) reclamation objectives that refer to establishment of the vegetative cover, increase in litterfall and decomposition, accumulation of organic matter, and soil fertility improvement. A decision to use a specific practice has also two types of outputs, i.e. (i) directly related to the farming household such as the accomplishment of a farmer's production objectives, and (ii) associated with environmental impacts such as increased vegetation cover and species diversity, enhanced nutrient cycling, and improved soil fertility.

As part of its environmental management plan, the Colombian gold mining company Mineros S.A performs reclamation of areas affected by its activities in the region of El Bagre, Antioquia. The main objective of this reclamation scheme is to support the livelihoods of farmers by establishing crops in more fertile areas while restoring heavily disturbed areas through tree plantations. The main motivation for the establishment of agroforestry farms by the mining company early in 2001 was to fulfill legal requirements through the creation of an environmental management plan. In the beginning, the mining company was committed to establishing agroforestry plots until 2008. During this time, staff from the mining company observed that the project outcomes were better than expected in terms of the welfare of the settlers and improvements in productivity of the disturbed land. Therefore, the mining company included as part of their environmental management plan the support of the families of the settlers through the establishment of agroforestry plots each year.

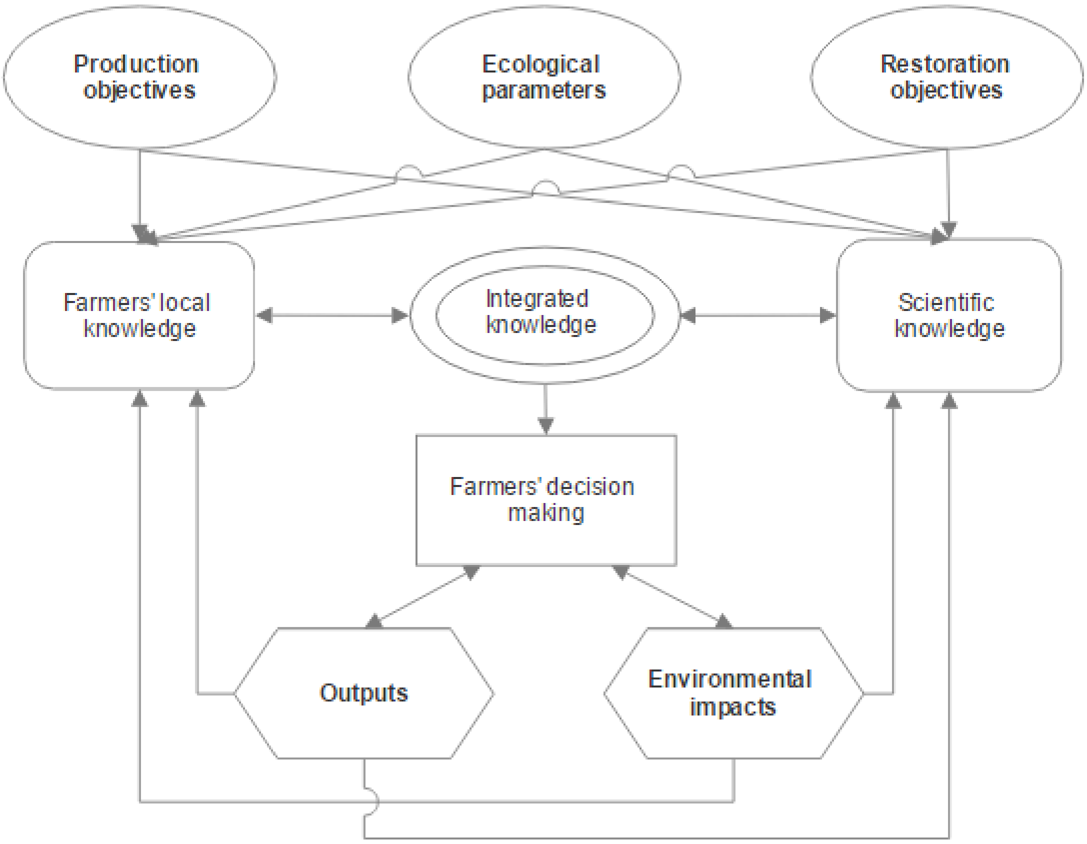

Figure 3.1. A conceptual framework for integration of farmer and scientific knowledge for management of areas affected by alluvial gold mining waste undergoing reclamation through agroforestry

Three agroforestry plots have been established by the company every year since 2001. The process begins with the entitlement of the land to the farmer. One of the entitlement conditions is that the socioeconomic condition of the family is unstable, i.e. it has no fixed source of income. In addition, the mining company looks for settlers who have long-term agricultural experience. The company provides construction materials and manpower for the construction of the house, basic sanitation facilities, and water and wastewater treatment systems. It also provides seeds and seedlings for the establishment of tree plantations and crops together with economic and technical support for the first three years of the reclamation process. It is assumed that the farmers will then be self-sufficient and able to derive a livelihood from their farms.

The mining company also provides technical support to the farmers with the help of agronomists to determine areas that are suitable for crop establishment, although the main decisions regarding land management are made by the farmers themselves. The farmers are trained in the use of agrochemical products, home orchards, solid waste management and occupational health among others. In addition, the corporate social responsibility of the mining company provides support to the farmers regarding the creation of associations and cooperative actions for activities like beekeeping. Furthermore, the corporate social responsibility staff provides training to the farmers on topics of entrepreneurship and leadership. In addition to the entitlement of the agroforestry plot, the mining company hires the farmers to perform reforestation activities in areas outside their farms. Furthermore, each farmer is given 5000 bags of seeds for the creation of plant nurseries to grow native trees that will be used for reforestation of disturbed areas.

Although this reclamation process has been going on since 2000, few controlled reclamation trials have been conducted, and there is still little understanding of the intrinsic factors associated with the nature of the deposits that might hinder the reestablishment of the vegetation cover or affect crop productivity. However, farmers and extensionists from the mining company have conducted many informal trials that have guided their reclamation efforts. Therefore, understanding their management practices and decision-making processes can significantly contribute to understanding how to improve the agricultural productivity of these deposits.

3.2 Methods

3.2.1 Site description

Gold mining in Colombia has taken place for centuries, the north-west part of the country, i.e. the departments of Antioquia and Choco, being the most important gold producers over the last 10 years (SIMCO, 2015). As a consequence of alluvial gold mining activities, large volumes of excavated sediments create waste deposits that cover the original soil and deplete its agricultural value (Shlyakhov and Osipov, 2004). According to the latest report published by the Colombian environmental authority in 2016, an area of 78,939 ha was affected by deposits due to alluvial gold mining. Around 8% of the total land affected by these deposits is located in El Bagre, a municipality of the department of Antioquia (UNODC, 2016).

El Bagre is located in north-west Colombia (Longitude: 7.793534 to 7.886321, Latitude: -74.804976 to -74.77886). The area lies in a humid tropical forest zone with an average temperature of 28°C and an annual precipitation of 2.000 - 4.000 mm. The dry season is from November to March and a rainy season from April to October. The average elevation is 45 m and the topography of the area is mostly flat with alluvial plains. The hydrology of the region is controlled by the Nechí River, its tributaries and a surrounding swamp complex. The habitat types are tropical humid forest and super-humid premontane forest. In a large area of the municipality, there is evidence of erosion, mostly generated by mining activities, that reduces the productivity of the land, and leads to soil destabilization, changes in the soil profile and loss of zones dedicated to agriculture (Ministerio del Trabajo, 2013). Vegetation cover is distributed as follows: 54.1% is forest (20% of this agrosilvopastoral system), 29% is herbaceous vegetation, 13% pastures, 3% bare soil, and less than 0.2% cropland (Ministerio del Trabajo, 2013).

The alluvial plains and the hills have been the most affected by gold mining by Mineros S.A. The company has established agroforestry plots to reclaim the waste deposits generated after alluvial gold exploitation with suction and bucket dredges. The aim of the company is to support farmers and their families through the establishment of crops, as an alternative to reforestation. In these parcels, agricultural and livestock species are combined to form multipurpose systems. More than 700 ha have been restored following this strategy, and more than 40 farmers and their families have benefitted.

3.2.2 Qualitative interviews

The target interview group comprised farmers that had received a reclamation plot from Mineros S.A and support from the extensionists from the mining company. Semi-directive interviews were used where discussions were guided by the interviewer, but the direction and scope of the interview followed the train of thought of the interviewee. This method was selected in order to give freedom to the interviewer to make clarifications and allow an in-depth investigation into the unique experience of the interviewees (Huntington, 2000).

The sample unit was the farm household where the head of the household or the person making management decisions was interviewed. Interviews comprised demographic data, soil-related information, and questions on the difficulties involved in performing agricultural activities in land disturbed by mining, crop rotation, agricultural inputs and fallow periods. Information was also gathered on the previous agricultural experience of the farmers. Soil-related questions were, for example: How would you describe the different soil types that occur in your parcel? How would you describe a good/fertile soil? How do you recognize potential cropping sites? How do you respond to crop failure? What do you think is more important for soil fertility improvement and successful cropping: reclamation time or management?

In total, 33 interviews were conducted in Spanish and 17 hours of conversation recorded. For the transcription of the interviews, the original wording of the interviewees was retained and analyzed by identification of themes. For each theme, a code was assigned to summarize the theme of a section of the transcript (Wengraf, 2001), and repeated themes were given the same code. To indicate the frequency and number of interviewees that mentioned a specific code, a superscript was assigned to the end of the sentence, the first number indicating the number of times a theme was mentioned, and the second number how many interviewees mentioned it. This gives an idea of the generality of a theme. The methodology was adapted from Botha et al. (2008).

3.2.3 Soil sampling

All interviewed household heads were asked to indicate their most fertile and infertile fields. From each field, soil samples were taken at a depth of 0-15 cm, air dried, homogenized and passed through a 2-mm sieve for chemical analysis according to (USDA, 2014). Soil pH was determined by the potentiometric method 1:1 water, organic matter by the Walkey-Black method and nitrogen by the Kjeldahl method. Available phosphorus was determined by a modified Bray-II method, while K, Ca, Mg, and Al were determined by atomic absorption spectroscopy. Soil physical analyses were performed using methods developed by Pla (2010). Soil texture was determined by the Bouyoucos hydrometer method.

3.2.4 Data analysis

To analyze the differences in soil physical and chemical properties between fields judged by the farmers as fertile and infertile, an analysis of variance was conducted in which soil properties were examined as a function of soil quality. Kruskal-Wallis tests were used to compare each soil parameter associated with fertile and infertile soils.

3.3 Results

3.3.1 Household characteristics

Out of the 33 interviewed farmers, only a few were women (6.1 %; Table 3.1). The age of the respondents ranged between 33 and 79 years, with an average of 45 years. The majority of the respondents (72.7%) were migrants from other municipalities in the region and from neighboring regions. Only a small share (6.1%) of the respondents was indigenous.

Table 3.1. Demographic characteristics of respondents (n = 33).

Demographic Characteristic									
Gender	%	Age group	%	Marital status	%	Educational status	%	Ethnic origin	%
Female	6.1	20-35 years	12.1	Married	87.8	Primary school	57.6	Indigene	6.1
Male	93.9	36-50 years	42.4	Divorced	6.1	High school	9.1	Locals	21.2
		51-65 years	39.4	Widowed	6.1	Technical degrees	3.0	Migrants	72.7
		>65 years	6.1			None	30.3		

3.3.2 Soil physicochemical properties

Significant differences were revealed through the analysis of the physical and chemical soil parameters of the soil samples from the fields classified by farmers as fertile or infertile (Table 3.2). The results of the analysis reveal a strong agreement between farmers’ perceptions and soil nutritional status. They also show that despite the heavily disturbed status, the soils are fairly fertile and thus suitable for agricultural production. However, the unfertile fields should be restored to improve the overall productivity of the farms. The physicochemical properties vary significantly between fertile and infertile fields (Table 3.2). The fertile fields had a higher content of N and organic matter, as well as of P, K, Ca, Mg and Na. The soil textures also varied significantly between fertile and infertile fields. The more fertile fields are associated with a higher silt and clay content in contrast to the infertile fields that had very high sand contents. These results evidence a strong agreement between the farmers’ assessment of soil fertility and the scientific assessment of soil physicochemical properties.

Table 3.2. Median values of soil properties of fields classified as fertile and infertile by farmers, with a non-parametric Kruskal-Wallis (KW) analysis of variance (n = 33).

Soil property	Fertile soil	Infertile soil	KW p-value
pH	4.8	5.3	0.002628
Al (cmol(+)/kg)	0.2	0	0.0007745
N (%)	0.18	0.06	0.0009447
OM (%)	3.83	0.87	0.0002522
P (mg/kg)	14	28	0.0003681
K (cmol(+)/kg)	0.14	0.09	0.0164
Ca (cmol(+)/kg)	3.76	0.99	0.0001963
Mg (cmol(+)/kg)	1.81	0.59	0.0003173
Na (cmol(+)/kg)	0.199	0.144	0.0001962
Sand (%)	41	91	3.137e-06
Silt (%)	34	3	1.715e-06
Clay (%)	17	6	0.0001844

3.3.3 Farmers' assessment of soil fertility

The farmers considered that the fertility of the farms depended on the quality of the materials deposited by the dredge[11,9†]. Soils that present greater challenges for reclamation are those that have been heavily washed by the dredges[9,7], specifically by

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[†] To indicate the frequency and number of interviewees that mentioned a specific code, a superscript was assigned to the end of the sentence, the first number indicating the number of times a theme was mentioned, and the second number how many interviewees mentioned it. This gives an idea of the generality of a theme. The methodology was adapted from Botha et al. (2008). Please refer to section 3.2.2 for further details.

suction dredges[5,2]. Farmers observed that the deposits created by bucket dredges were the most suitable for crop establishment[2,2] and revegetated faster[2,2], therefore the productivity of the reclamation plots would be much higher if suction dredges were not used[1,1].

Farmers often described fertile areas of the deposits as those that had a higher sediment content [65,28], i.e. particles smaller than sand, namely a mixture of silt and clay. Therefore, the identification of potential cropping sites is mostly done by detecting the areas of the plot that have observable higher sediment content[11,9]. Moreover, the farmers also observed that the color of the sediments is also a relevant feature to determine the fertility of the soil. For example, yellow sediments can be only used to plant fruit trees, but in the dry season they get very dry and lower the productivity of the trees[3,2]. Furthermore, the grey or red sediments dug by the dredge might not be suitable for cropping because they are very compact and do not allow the water to penetrate[3,1].

The color of the soil is also an indicator of fertility, for example, brown and black soils are considered as more fertile[3,3], whilst light colored sand is associated with non-fertile areas[4,2]. The presence of sediments carried by the river in flood-prone areas is also associated with soil fertility[28,18]. Farmers observed that the sediments from the river act as fertilizer[16,13], therefore after flooding the soil would be suitable for establishing crops.

Deposits with a high sand content are not suitable for crop establishment [91,28]. The main problem here is that in the dry season, high soil temperatures kill the plants [9,7]. In order to establish vegetation in sandy areas, furrows need to be made for the seedlings, and soil with a high clay and silt content needs to be applied along with mineral fertilization[3,3]. However, below the sandy layer sediments sometimes exist and plants can establish without the need of further fertilization.

Cecropia peltata (Urticaceae)^{14,14} and *Calathea lutea* (Marantaceae)^{10,10} are the most common indicators that farmers use to determine the suitability of the soil for crop establishment (Table 3.3). *Paspalum fasciculatum* (Poaceae) is an indicator of good soil quality,^{8,7} because it is associated with soil freshness, which refers to lower temperatures and higher moisture during the dry season. In addition to vegetation, farmers reported the presence of worms as an indicator of soil suitability for the establishment of crops^{3,3} and vegetables^{1,1}. The farmers are aware that worms improve soil fertility through fertilization,^{2,2} and help the plants through increased porosity, thus reducing the effects of compaction^{1,1}.

Table 3.3. Species used by farmers as indicators of soil suitability for agriculture.

Local name	Scientific name	Attributes
Yarumo^{14,14}	*Cecropia peltata* (Urticaceae)	Soil recovery^{1,1} Sediments presen1^{1,1} Soil suitable for subsistence crops^{1,1} Indicates end of fallow period^{1,1}
Bijao^{10,10}	*Calathea lutea* (Marantaceae)	Soil suitable for subsistence crops^{3,3} End of fallow period^{1,1}
Gramalote^{5,5}	*Paspalum fasciculatum* (Poaceae)	Soil freshness in dry season^{2,2}
Canutillo^{3,3}	*Commelina erecta* (Commelinaceae)	Nutrient-rich soil^{1,1} Indicates water availability^{1,1}
Santamaria^{2,2}	*Tanacetum balsamita* (Asteraceae)	Good to feed cattle^{1,1}
Zarza^{1,1}	*Rubus ulmifolius* (Rosaceae)	Soil suitability for subsistence crops^{2,2}
Lengua de vaca^{1,1}	*Sansevieria trifasciata* (Asparagaceae)	Sediments present^{1,1}
Iraca^{1,1}	*Carludovica palmata* (Cyclanthaceae)	Soil suitability for subsistence crops^{1,1}
Papayote^{1,1}	*Cochlospermum orinocense* (Bixaceae)	Nutrient-rich soil^{1,1}

Local name	Scientific name	Attributes
***Mortiño*[2,2]**	*Vaccinium meridionale* (Ericaceae)	Nutrient-rich soil[1,1] Indicates soil exhaustion[1,1] Soil not suitable for crop establishment[1,1]
***Ñipi-ñipi*[1,1]**	*Sapium haematospermum* (Euphorbiaceae)	Soil suitability for subsistence crops**[1,1]**
***Balsa*[2,2]**	*Ochroma pyramidale* (Malvaceae)	Soil suitability for subsistence crops**[2,2]**

3.3.4 Farmers' fertility management practices

The extensionists of the mining company do not encourage the use of mineral fertilizer because the water retention capacity of the deposits is very low. Rain will, therefore, wash out the fertilizer thus reducing its effectiveness[2,2]. Alternatively, they encourage the use of organic fertilizers,[2,2] and educate the farmers regarding composting techniques. In spite of these recommendations, the farmers consider that mineral fertilization is needed[12,11] for crops such as maize and rice, as well as for plantain to improve productivity and quality of the harvested fruits.

Farmers perceive that litterfall[20,13] and decomposition[9,9] play a crucial role in the reclamation of soil fertility. They also noted that areas of the deposit that were not suitable for crop establishment when they arrived at the farm can now be used for this purpose due to litterfall[6,6]. Farmers rely only on tree litterfall as a source of fertilization[7,7] and consider that litterfall only is enough to improve soil productivity. Litter from selected trees is also used to cover the tree pit of recently planted fruit trees[1,1].

The extensionists of the mining company suggest planting *Mucuna pruriens* (Fabaceae) and *Pueraria phaseoloides* (Fabaceae) as green manure for the reclamation of areas that exhibit low productivity, i.e. mostly areas with a high sand content or gravel deposits with low sediment content. Farmers observed that *P. phaseoloides* has the ability to grow in areas with low fertility[24,18], and is used to promote soil recovery[12,12]. They also used it as green manure for lemon trees,[1,1] cassava,[1,1] and plantain[1,1], for fallow periods[4,4], to reduce soil compaction in areas that might be suitable to plant subsistence crops[1,1], for weed management[1,1] and for cattle feeding[3,3]. The farmers observed that *M. deeringianum* has the ability to grow in areas with low fertility,[26,17] and is useful to promote soil recovery[13,13]. *Mucuna deeringianum* is also used as green manure for cassava and yam crops[1,1], for weed management[1,1] and as a cover crop for fallow periods[5,5]. The plant can easily be eradicated by cattle, therefore farmers consider that *P. phaseoloides* is better for farms with cattle given its fast regrowth[3,2]. On the same line, the extensionists of the mining company suggest the use of *M. deeringianum* for intercropping with fruit trees and plantain to improve yield[1,1]. However, as it is a climbing legume, cutting intervals of two weeks are required to prevent it from becoming the dominant crop[1,1].

The extensionists of the mining company also suggest always using *M. deeringianum* and *P. phaseoloides* for fallow periods. Farmers prefer to allow spontaneous vegetation to grow during fallow periods[30,16] instead of using these legumes because removing these species is a demanding task,[1,1] and also because of seed availability[2,2].

3.3.5 Grazing

For grazing, the extensionists of the mining company suggest a maximum of 10 cattle per farm[2,2]. For this purpose, species like *Chrysanthemum maximum* (Asteraceae), *Alocasia macrorrhizos* (Araceae) and *Saccharum officinarum* (Poaceae) have been introduced[1,1]. The extensionists state that the deposits cannot be dedicated to grazing due to the instability of the soil and risks of increased erosion[2,2]. However, farmers perceive cattle as their main source of income[14,9], because the profit from crops growing on the deposits is not enough to fulfill their needs[14,9]. Of the 33 interviewed farmers, 18 farmers had 8-45 cattle each, 8 farmers wanted to have cattle in the near future, and 7 farmers did not have cattle and did not plan to have any in the future.

Regarding the impacts of grazing on fertility and reclamation of the soil, the perceptions differ. Some farmers perceive that cattle improve soil fertility through manure as fertilizer^{12,12}, weed removal^{6,6} to prepare areas for cropping^{4,4}, trampling to improve soil stability,^{2,2}and seed dispersal^{1,1}. In contrast, other farmers perceive that grazing does not improve soil quality because trampling causes soil compaction^{3,2}, manure might promote weed growth,^{2,2} and tree plantations for reclamation are reduced^{2,2} as more areas are dedicated to pastures.

Areas designated for grazing are usually natural soils of the farmland^{4,4}, flood-prone areas^{3,3}, areas in which grasses grow spontaneously^{7,6}, or areas that are not suitable for crop establishment^{4,4}. Farmers have also decided to assign both fertile and infertile areas to grazing^{3,3} so that cattle can be fed in the fertile areas where pastures are more abundant while fertilizing the infertile areas through their manure.

3.3.6 Challenges for crop establishment and revegetation

The extensionists of the mining company perceive that the heterogeneity of the deposits is very high, and significant variability can be observed even at distances of less than 5 m^{1,1}. Due to this high heterogeneity, they do not consider mono-cropping a suitable land-management scheme^{1,1}, because crops need to be selected depending on the variation of the characteristics of each deposit. Along the same line, farmers consider that the variability of the deposits is much higher than the variability of natural soils^{5,5}. Therefore, they perform informal experiments^{18,15} in areas that exhibit different properties to determine which crop is suitable for which area of the farm. In addition to the variation of soil properties within their farms, farmers need to consider seasonal variation in their experiments, because in some areas crops might be productive during the rainy season but might reduce yield or die during the dry season^{29,14}.

When the farmers arrive on their land they need to get familiarized with the highly varying properties of the deposit in the area of their farm. The staff of the mining company suggests building the farmhouse in the less fertile area, specifically with a high sand content, to save fertile areas for agriculture. However, the farmers usually build their houses close to their crops[2,2], close to the river for easier access to transport,[5,5]and in areas not prone to flooding during the rainy season[4,4].

3.3.7 Weed and pest management

Farmers also observed that the occurrence of pests affecting their crops is more frequent in the deposits compared to their previous farming experience in natural soils[9,9]. They also found that the deposits were more prone to weed invasion than natural soils[8,8], therefore establishing crops on the deposits implied higher expenses associated with weeding and herbicides[5,4] with lower yields due to lack of nutrients in the soil[7,5].

The mining company does not encourage the use of pesticides and herbicides, but occasionally provides herbicides to prevent the farmers burning the fields in preparation for crop establishment. Lorsban® is the most frequently used pesticide,[14,13] mostly against the ants[15,11] and termites[17,13] that are the most frequent pests in the areas. Burning is occasionally done before seeding to prevent mice from eating the seeds[2,2]. After the fruit has developed, the mining company does not provide any other type of pesticide and does not encourage its use.

3.4 Discussion

3.4.1 Local indicators of soil fertility

Waste deposits left by suction and bucket dredges are leveled following basic technical recommendations concerning reclamation of waste dumping sites. Such dumps usually have undulating surfaces with wet patches and shallow water, and periodically drying sites (Vetluzhskikh, 2010). The uppermost layer is usually characterized by a high porosity and very low soil content. As a consequence, these surfaces have a high water infiltration capacity, which leads to leaching of nutrients and small soil fractions. Contrasting temperature conditions also exist, with surface heating on sunny days and deep cooling during the nights (Shlyakhov and Osipov, 2004). These are all unfavorable conditions for the development of vegetation. Therefore, one of the major challenges that the farmers face is the identification of areas that can be suitable for crop establishment. The farmers also need to identify a reclamation strategy for areas not suitable for crops, namely areas for reforestation and cover crops.

Farmers usually identify potential cropping areas based on soil texture, more specifically on clay and silt content. There is considerable evidence indicating that fine-textured soils have a higher content of organic carbon and nitrogen than coarse-textured soils. Fine-textured soils provide physical protection to organic matter, given their ability to associate with clay and silt particles (Hassink, 1997). The color of the soil is also an indicator of its drainage capacity. Yellow indicates that the soil is well-drained, whereas grey implies poor drainage (Bigham et al., 1978). As a consequence, yellow soils, due to their poor water holding capacity and lack of organic matter, can mean unfavorable conditions for plant development during the dry season. On the other hand, poorly drained soils compact during the dry season leaving little oxygen for plant roots consequently affecting plant growth (Gilman, 2015). Red soils indicate low organic matter content and significant amounts of iron oxides and hydroxides, which is a sign of soil weathering. Highly weathered soils have low water and nutrient retention capacities and strong acid reactions, therefore they can only support the growth of plants with low nutrient demand and high tolerance to acid conditions (Soil Water Management Research Group, 2003).

In addition to the color and texture, farmers observed that flood-prone areas are more fertile, and mentioned that sediments from the river act as fertilizer. There is evidence that flooding events markedly influence soil fertility. Flooding events can increase the availability of nutrients through changes in redox potential and also through the influx of dissolved and suspended nutrients (Visser et al., 2003). However, flooding events might restrict oxygen entry into the soil and reduce the rate of respiration and nutrient absorption in plants. The overall positive effect of flooding observed by the farmers might be an effect of brief pulses of nutrients associated with wetting of the soil (Ogden et al., 2007) and the nutrient load of the flood water.

Farmers avoid areas with a high sand content due to the extreme temperatures and low water availability during the dry season. It is well known that sandy soils have a low water holding capacity and retain few nutrients (FAO, 1979). The sandy fractions of soils are dominated by quartz, which as an inert soil component with limited surface charge has a very limited capacity to retain water and nutrients. Research has shown that surface layers of sandy soils can be extremely water repellent when dry. Water repellency affects the way in which rainwater penetrates the soil inducing preferential flow paths (Bisdom et al., 1993). The variation of soil temperature depends on the porosity of the soil among other factors. Therefore, the temperature in sandy soil varies more randomly than in other soil types, given that pores allow an easy permeation of radiant heat absorbed from sunlight and air from the surface to lower layers (Nwankwo and Ogagarue, 2012), which might affect plant growth during the dry season.

In addition to soil properties, farmers also observed the presence of specific plant species as local indicators of soil fertility. Plants that grow spontaneously in the areas and that exhibit vigorous growth are usually good indicators of fertile soils (Soil Water Management Research Group, 2003). *Cecropia peltata* was identified in a study conducted by Pauli et al. (2012) in which farmers in Honduras used this species as an indicator of fertile soils. However, it is stated that *C. peltata* can be detrimental to crop growth because it tends to attract insect pests and has large leaves that can damage crop seedlings through litterfall (Pauli et al., 2012). Barrios et al. (2003) also documented the use of *Cecropia* sp. and *Paspalum fasciculatum* in the Orinoco floodplains as indicators of good soil quality.

3.4.2 Soil fertility management and reclamation

Management can vary greatly from farmer to farmer, and it is increasingly being recognized as a crucial factor underlying farm operations. Therefore, management of soil fertility depends on strategies that farmers use to achieve their goals and depends on available resources and personal attitudes towards risks and family life. Analyses of farmers' decision-making processes performed by social scientists in tropical regions show that decisions regarding a practice, namely soil fertility management and agroforestry, usually consider the context of the whole farm and resources available to the farmer, which include available labor, availability of fertilizer and other agrochemicals, entire landholding, characteristics of the fields, access to water, access to machinery or animal traction, and access to other off-farm resources such as forested lands or woodlots (Schroth and Sinclair, 2003). In addition, farmers focus on trade-offs between efforts to meet the production objectives and the payoffs expected from these efforts.

Mineral and organic fertilizers are used by most farmers to improve productivity and quality of the harvested fruits. In contrast, some farmers rely only on litterfall as a source of fertilization and consider it is enough to improve soil productivity. Litterfall production and decomposition have been widely acknowledged as a crucial step for soil recovery and improvement of biological diversity in disturbed lands, given that they promote the reactivation of the biogeochemical cycles. This reactivation triggers an increase in organic matter and nutrient availability, regulates the pH, improves aggregate stability, and increases soil water holding capacity (Leon, 2012). Furthermore, for reclamation of areas covered by waste generated by alluvial gold mining, the role of litter is especially important. In addition to the reclamation of biogeochemical cycles, litterfall has proven to improve root distribution, water use, surface temperature, and habitat suitability for micro-wildlife (Mummey et al., 2002).

Farmers clearly confirmed the role of litterfall and its decomposition in restoring soil fertility. In some cases, they also use litter from selected trees as a cover to protect recently planted fruit trees. Moisture content is one of the critical factors regulated by the thickness of litter layers, especially in mining areas undergoing reclamation (Sheoran et al., 2010). Accumulation of leaf litter and its decomposition increase the level of organic carbon in soil and promote plant growth (Maiti and Ghose, 2005). In addition, litter decomposition creates a favorable microclimate for soil microbes responsible for the breaking down of plant biomass (Lawrey, 1977).

Nitrogen is usually a major limiting nutrient in mine spoils, therefore, regular nitrogen fertilization is required to maintain healthy vegetation growth (Yang et al., 2003). Therefore, a suitable alternative is to introduce legumes and other nitrogen-fixing species. In areas that farmers consider not suitable for crop establishment, *Mucuna deeringianum* and *Pueraria phaseoloides* are used as green manure to restore soil productivity. *Pueraria phaseoloides* and *M. deeringianum* have also been used as green manure for some fruit trees and crops, as well as for weed management. Such species can have a strong effect on soil fertility through the production of nutrient-rich litter that is easily decomposable, as well as through the turnover of fine roots and nodules (Sheoran et al., 2010). In addition, the mineralization of nitrogen-rich litter from these species allows substantial transfer of nitrogen to companion species, enabling the development of self-sustaining ecosystems (Singh et al., 2002). *Pueraria phaseoloides* and *M. deeringianum* have so far exhibited the desired features for planting on waste deposits for reclamation, i.e. ability to grow on nutrient-poor and dry soils, rapid development of vegetation cover and biomass accumulation, improved soil organic matter and enhanced supply of plant-available nutrients (Singh and Singh, 1999).

Most of the farmers in the area already raised cattle or planned to do so in the near future. The majority perceived that cattle improved soil fertility in areas not yet suitable for crop establishment through manure as fertilizer, weed removal and improvement of soil stability. However, they also perceived that trampling compacted the soil, could promote weed growth and affected the reclamation process given that more areas are dedicated to pastures instead of tree plantations. Grazing can be seen as suitable for rehabilitating mine land due to the lower soil productivity that is required compared to cropping. Maczkowiack et al. (2012) determined that grazing is likely to be a post-mining land use that represents a low risk. However, factors such as grazing intensity, climatic conditions, biophysical capability of the land, and farmers' attitude to land management should be considered when analyzing the risk of grazing (Maczkowiack et al., 2012). The authors also consider that mining companies can take specific steps to support grazing as a sustainable post-mining land use by purposefully directing rehabilitation towards the achievement of biophysically productive rehabilitated areas. Furthermore, Byrne (2005) observed that pastures established on rehabilitated mine land have the potential to be just as productive as natural pastures, however, the selection of areas for pasture should be done carefully due to the high variability of the conditions of the soil.

3.4.3 Comparison of soil physicochemical characterization and farmers' perception of soil fertility

Parallel studies were conducted to compare the scientific assessment of soil fertility and soil classification with typologies developed by local farmers (Ali, 2003; Barrera-Bassols et al., 2009; Dawoe et al., 2012; Gray and Morant, 2003; Karltun et al., 2013). These studies share the common conclusion that there is a good agreement between the knowledge that farmers possess on soil fertility and the scientific indicators. Farmers possess a broad knowledge of processes such as litter decomposition, soil biology, nitrogen fixation (Grossman, 2003) as well as on soil types and characteristics, which match very well with scientific classifications (Grossman, 2003; Nath et al., 2015).

Farmers working in the study areas undergoing reclamation develop a complex scheme for decision making given the disturbed status and high intrinsic variability of their fields. They classify their land on the basis of soil texture and color, moisture conditions and presence of indicator plant species to determine suitability for crop establishment. They also recognize the importance of flooding for soil fertility and create a management strategy based on seasonal variations in their fields. Furthermore, there is a significant similarity between farmers' knowledge of soil fertility and the physicochemical assessment of soil properties. These were significantly different between fertile and infertile fields, which reveals a close correlation between farmers' soil knowledge and soil physicochemical conditions.

3.4.4 Integrating scientific and local knowledge for soil management in areas undergoing reclamation

Farmers have a deep understanding of their farmlands and possess vast knowledge of soil management. Depending on the pedological conditions of their fields, they develop cropping strategies to meet their production objectives (Ali, 2003). However, sustainable soil management should ideally consist of a technical understanding of the principles of soil management provided by scientific knowledge complemented with an intuitive local knowledge, which would allow the interpretation of the scientific knowledge in a local context (Ingram, 2008). Farmers who are aware of the consequences of their activities for the environment are likely to behave in an environmentally friendly manner and seem more concerned by cooperation with other stakeholders of the landscape (Vuillot et al., 2016). Furthermore, research has shown that farmers who belong to groups such as farmers associations are more successful in managing their crops, and in acquiring knowledge regarding management of pests, crop rotation and improvement of planting materials (Adam et al., 2015).

The farmers also have knowledge of strategies for improvement of soil quality and about the reclamation of disturbed soils (Moges and Holden, 2007). They usually define soil quality as a combination of factors such as crop growth and productivity, nutrient status, weed species and visual criteria. These indicators play an important role in their decision making regarding the use of appropriate management strategies (Tesfahunegn et al., 2016). The farmers are also aware of soil fertility decline processes and land deterioration due to grazing and uninterrupted cropping. In response to these problems, they develop management practices that are supported by their previous experience in land management and years of working on severely disturbed lands. These strategies are fallowing, use of cover crops, intercropping with nitrogen-fixing species, among others (Engdawork and Bork, 2016).

To improve the management practices, it is necessary to expand extension services and farmer education opportunities in the area, which could also be achieved by promoting the interaction of the scientists working in the area with farmers and extensionists. One approach could be to create communal demonstration plots where farmers can collectively learn how to better manage and protect their crops (Adam et al., 2015). This would not only allow knowledge acquisition by the farmers but would also promote knowledge exchange among more experienced farmers with the newcomers.

It is clear that local knowledge is vital to understand the dynamics of the reclamation process. However, farmers understand soil management in a holistic manner that does not distinguish processes in the reductionist way that scientific assessment allows (Moges and Holden, 2007). They are usually interested in soil productivity and appropriate management practices and usually, take only the topsoil into account to analyze indicators of fertility. On the other hand, scientific research approaches to soil fertility from the perspective of soil formation, nutrient content and other measurable factors. Nevertheless, farmers and researchers share the same objective, which is to ensure that soil resources are capable of meeting present and future needs (Desbiez et al., 2004). Therefore, there is a need to complement local knowledge with relevant scientific advice (Barrios and Trejo, 2003) to rehabilitate the land not only based on a traditional land management approach but also focused on raising its agricultural productivity.

3.5 Conclusions

The findings of this study suggest that farmers performing agroforestry in areas covered by alluvial gold mining waste rely mostly on their own local knowledge, which is holistic yet not specific, where each farmer has found a way to respond to the challenges that the heavily disturbed conditions of the area pose to crop establishment. However, the farmers are receptive to the ideas provided by the extensionists, which shows that there is room for external actors such as scientists and development actors to intervene through knowledge transfer to the farmers. Moreover, it is necessary that extensionists develop management schemes that truly integrate farmers' perceptions regarding the management of their fields. Farmers' knowledge of soil and management practices plays a significant role in sustaining farm productivity and soil fertility. Especially farmers in areas covered by alluvial gold mining waste develop a complex scheme for soil management to meet their production goals given the disturbed status of their fields and the challenges that this status represents.

Farmers' understanding of the complexity of their fields influences their farming practice, thus increasing their awareness of the inherent heterogeneity of their fields. Interdependencies between management practices and improvement of soil fertility may be a good strategy to increase the acceptance of the management guidelines provided by extensionists. Furthermore, the creation of spaces that promote cooperation between more experienced farmers and those who are new to the restoration process will enrich and facilitate the adaptation of management strategies. The findings also imply that expansion of extension services and education opportunities for farmers in the area is required, not only to provide support to the farmers but also to create cooperation of farmers with scientists working in the area.

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4. CHANGES IN TECHNOSOL PROPERTIES AND VEGETATION STRUCTURE ALONG A CHRONOSEQUENCE OF REVEGETATION OF WASTE DEPOSITS IN AREAS WITH ALLUVIAL GOLD MINING[♦]

Abstract

Alluvial gold mining, particularly dredging operations, produces two types of waste: (i) gravel mixed with low percentages of sand, silt and clay, and (ii) sand deposits, composed mostly of sand. Waste deposits are pedologically classified as Technosols, which usually have low nutrient levels, low pH and high infiltration rates that hinder the spontaneous reestablishment of vegetation. One approach that has been used for revegetation of Technosols is the establishment of agroforestry systems in which trees, agricultural crops and livestock are combined for the reestablishment of an ecologically and economically viable land-use system. The aims of this study are (i) to investigate whether the variability of deposit properties is influenced by time period since establishment, type of deposit material (gravel or sand deposit) and sampling depth, (ii) to investigate if the variability of size structure of the new plant cover was affected by the time period since establishment and deposit type, and (iii) to determine which soil parameters correlate best with the size structure distribution of vegetation across different time periods since establishment of the revegetation plots. The findings suggest that the variability of Technosols is primarily influenced by the parent material of the alluvial gold deposits and by the technology used for gold mining, i.e. bucket or suction dredges that determine the type of deposits formed. Changes in vegetation structure were observed among areas with different time periods (0-12 years) since establishment. The lack of significant changes in the physicochemical properties of the deposits reflects, however, the long-term processes changing belowground compared to aboveground compartments. The Technosols formed after alluvial gold mining

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activities exhibit nutrient contents and structural properties that make them suitable for agricultural use. They can ensure essential functions for rural areas such as woody biomass production and crop establishment. Yet future productivity might be increased if deposits are managed according to specific agricultural purposes and crop selection is based on the site-specific properties of each deposit.

4.1 Introduction

Alluvial gold mining, particularly dredging operations, leaves a vast amount of waste that covers the natural soil, destroys riparian ecosystems, and impacts river beds and valleys (Shlyakhov and Osipov, 2004). Once the exploitation of alluvial deposits using suction and bucket dredges has come to an end, the dredges are transferred to a new working front leaving behind three elements: (i) gravel deposits that consist of rock fragments coming from material extracted by bucket dredges, (ii) sand deposits that consist of sand from material extracted by suction dredges, and (iii) artificial wetlands that remain after the exploitation of the deep alluvium of the river and surrounding swamps. Deposits created by alluvial gold mining usually have low macronutrient levels and an acidic pH that tend to disrupt soil formation processes and plant growth (Cooke and Johnson, 2002). There is also a discontinuity between the upper and lower profiles of the soil due to the superposition of the waste over the natural soil (Wahsha and Al-Rshaidat, 2014).

The deposits formed after alluvial exploitation are classified as Technosols given the human influence exerted on them and the fact that their properties and pedogenesis are dominated by their technical origin (IUSS Working Group, 2014). Even if the composition of Technosols is in principle different to the composition of natural soils, their pedogenesis might not be that different. Therefore, it is important to analyze the extent of the pedogenesis of Technosols over periods of time based on changes in physicochemical, hydraulic and morphological properties (Jangorzo et al., 2013).

To mitigate the environmental impact of alluvial gold mining, over the last two decades, frequent attempts were made to revegetate gravel and sand deposits left by dredges. For instance, the Colombian company Mineros S.A. established agroforestry systems to revegetate gravel and sand deposits created after alluvial gold exploitation with suction and bucket dredges. Agroforestry systems are here defined as the growth of woody perennials on the same management unit (farm) as used for agricultural crops and animal husbandry, with both ecological and economical interactions between the woody and non-woody components of the system (Nair, 1993). Multipurpose trees are often planted on cropland, around homesteads, as shelterbelts or for revegetation of less fertile areas. Farmers commercialize the timber, use it as firewood and often do tree beekeeping. The aim of the company is to support agricultural land use by establishing crops in more fertile areas of the deposits while creating productivity on less fertile areas by planting trees. So far, under the Mineros S.A. initiative, more than 700 ha have been restored in this way, and more than 40 farmers and their families have benefitted by the entitlement of 14-ha plots. However, the establishment of agroforestry systems is not an easy task, due to the nature of the deposits that often poses extreme challenges for plant growth.

Although revegetation of Technosols is a long-term process, the ability to interpret early signs of revegetation success or failure is desirable for management (Gould, 2012). Therefore, efforts should be made to understand vegetation and soil development at the early stages of the revegetation process. For this, several indicators have been studied, e.g. temporal trends of soil properties (Hendrychova, 2008), microbial communities (He et al., 2012), plant communities (Holl, 2002), vertebrate communities (Nichols and Grant 2007), and landscape functionality (Antwi et al., 2014). One approach to characterize transformations of Technosols typically involves the arrangement of a chronosequence consisting of sampling and measurements in recently deposited materials and contrasting the results with those of Technosols developed a long time ago. Yet Technosols are very heterogeneous, and the properties of each area of the deposits depend on many factors like the technology used for gold mining or the rate of weathering processes. Therefore, transformation processes have to be interpreted with care (Uzarowicz et al., 2017).

The structure of vegetation is sensitive to edaphic factors such as soil texture, moisture content, bulk density, organic matter and nutrient content. These factors influence plant development and regulate community structure and ecosystem functioning (Juwarkar et al., 2013). Soil structural stability influences both plant growth and community composition due to its relationship with other physical soil properties related to water availability (Heneghan et al., 2008). Water storage capacity, bulk density and porosity are closely linked to soil structure. Soil with a higher content of silt and organic matter usually has a good structural stability for supporting plant growth, while soil resistance to erosion increases with clay content (Zhang et al., 2015). Furthermore, comparing plant community resemblance between different sites or the progressive change over time can provide a sensitive measure of ecologically relevant changes in the environment (Philippi et al., 1998). One approach to achieve this is to determine community resemblance based on size structure. According to Cáceres et al. (2013), in plant communities, the most natural structural variables for wood vegetation are plant height and trunk diameter. Abundance profiles of the plant community for a given area can be calculated with the values of the structural variables for each individual.

The main objective of this study was to analyze the variability of soil properties explained by the time period since revegetation as well as sampling depth and deposit type, and to integrate the soil data with the analysis of the development of vegetation size structure across different time periods since the onset of the revegetation attempt. Furthermore, the set of physicochemical soil properties that correlated best with dissimilarities of community size structure was determined.

4.2 Material and methods

4.2.1 Study area

The study site is located in northwest Colombia in the gold mining area of El Bagre, Antioquia (Figure 4.1). The area lies in the humid tropical forest zone with an average temperature of 28°C and an annual precipitation of 2,000 – 4,000 mm. The region has a dry season from November to March and a rainy season from April to October. The topography is mostly flat with the characteristics of a low-lying forest that remains flooded most of the year, thereby preventing productive activities in agriculture, animal husbandry or forestry. Such areas are the most affected by gold mining. Revegetation initiatives begin by flattening the topography with bulldozers in order to reduce the slope to below 30% for the subsequent establishment of a vegetation cover. Revegetation areas established in 2002, 2006, 2010 and 2014 were selected for this study. Six sampling sites were chosen within each of the four different areas giving a total of 24 sampling sites with 12 located in gravel deposits and 12 in sand deposits.

The revegetation efforts of the mining company Mineros S.A. focus on gravel and sand deposits. From the total area that needs to be restored, depending on the location and stability of the deposits, specific areas were selected to implement the agroforestry systems. Farmland is allocated to beneficiaries that meet the requirements of the company, and partnership agreements are signed. Mineros S.A. provides resources for crop establishment and reforestation such as seeds and seedlings as well as economic and technical support to the sharecroppers at the beginning of the revegetation process.

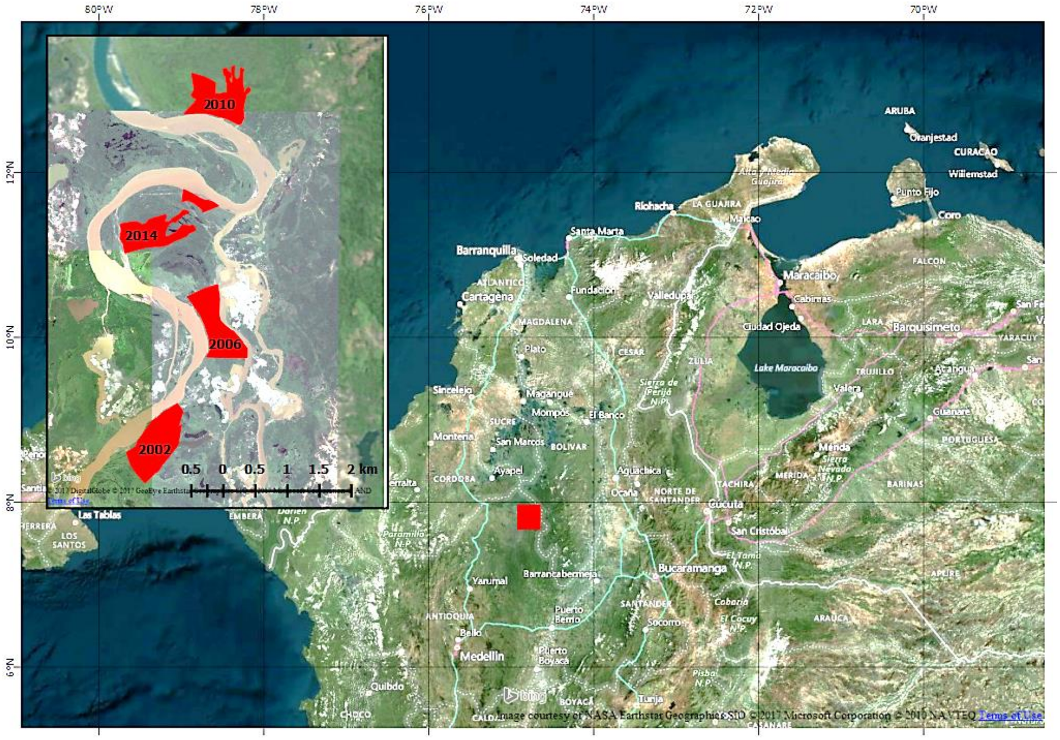

Figure 4.1. Four areas in El Bagre, Antioquia, Colombia, covered by gold mining waste deposits undergoing revegetation through agroforestry since 2002, 2006, 2010 and 2014 selected for soil sampling and vegetation measurements.

4.2.2 Soil sampling and analysis

Soil samples were collected from September 2015 to February 2016 at depths of 0-20 cm, 20-40 cm and 40-60 cm. For soil sampling, an area of 10 m x 10 m was selected at each sampling site to perform field measurements of hydraulic conductivity, percolation, description of the soil profile, and sampling for physicochemical analysis. For soil sampling, an auger with 10 cm diameter was used for sand deposits and a shovel for gravel deposits. Soil samples were passed through a 2-mm sieve and air dried for subsequent analysis.

Soil pH was determined by the potentiometric method 1:1 water, organic matter by Walkey-Black, and nitrogen (N) by the Kjeldahl method. Available phosphorus (P) was determined by a modified Bray-II method. Potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and aluminum (Al) were determined by atomic absorption spectroscopy. Soil physical analyses were performed according to the Pla (2010) protocol. Soil texture was analyzed using the Bouyoucos hydrometer method.

Samples for bulk density were taken as undisturbed soil cores from each sampled surface layer. Bulk density was estimated with oven-dry cores (105°C for 48 hours). Hydraulic conductivity was measured using a tension infiltrometer (Eijkelkamp, Netherlands) and a Guelph constant head permeameter (Eijkelkamp, Netherlands). Altitude, longitude and latitude were recorded using a portable GPS (Garmin eTrex 10, Germany). Saturated water content, field capacity and permanent wilting point were determined according to Richards and Weaver (1944). The structural stability index was determined following Yoder (1936).

4.2.3 Micro-morphological analysis

Soil-pit profiles were studied following the guidelines developed by the US?? Soil Science Division Staff (2017). The soil profile was divided into horizons, and each horizon was described according to the field-description handbook of Loaiza (2015) for the following properties: presence of roots, root size, particle shape, particle size, color, structure, consistence, and stoniness. For the soil color description, Munsell color charts were used (Munsell 2013), and for the mineralogy analysis in the field, 10x – 20x lenses were used.

4.2.4 Vegetation survey

The measurement of the size structure of vegetation was conducted on the 24 sampling sites according to González et al. (2006). Trees and shrubs were georeferenced within the boundaries of the 10 m x 10 m plots, and diameter at breast height (DBH), as well as total height of each live individual, was measured. Tree heights were measured with a Vertex IV hypsometer (Haglöf, Sweden).

4.2.5 Data analysis

Soils of anthropogenic origin are usually formed by an abundance of technogenic artifacts which makes them characteristically heterogeneous. This heterogeneity needs to be taken into account to select adequate methods for the statistical analysis of the data. For example, many hypothesis tests rely on the assumption of a normal distribution of the population. In the case of this study, the data was strongly non-normal and resistant to transformation. Nonparametric tests rely on the assumption that the samples are independent and come from the same distribution, and are usually less powerful than the corresponding parametric tests when the normality assumption holds. Nonparametric tests often require modifying the hypothesis, as the tests about the population center are about the median instead of the mean, which does not answer the same question as the corresponding parametric procedure (McArdle, Anderson 2001; Anderson 2001). In spite of this drawbacks, the use of nonparametric procedures was chosen as the best option for this study, as the sample size was in some cases not adequately large to perform parametric analyses with strongly non-normal data. A three-way permutational analysis of variance was conducted in which soil properties were examined as a function of the time period since revegetation, sampling depth and deposit type (gravel or sand deposit). P-values were calculated on 10,000 permutations of the data using the *adonis* function in the R *vegan* package (Oksanen et al., 2017). Kruskal-Wallis tests were used to independently compare each soil parameter associated with each deposit type. A linear discriminant analysis was performed (Huberty and Morris, 1989) to identify which soil properties contributed most to differences between gravel deposits and sand deposits. For this analysis, the variables were standardized and absolute weights used to rank soil properties in terms of their discriminating power, where the soil properties with large weights were considered as those that contributed the most to differences between deposit types. This analysis was performed using the *lda* function of the R package *MASS* (Venables and Ripley, 2002)

Abundance profiles of live plants were calculated for each plot to analyze the distribution of plant sizes. Based on the method developed by Clarke and Ainsworth (1993), an analysis was performed to identify the combination of soil properties that best explained the patterns observed in the size distribution of the vegetation community. For this, the *bioenv* function of the R package *vegan* was used to identify the most suitable subset of soil physical, chemical and hydraulic properties that best correlated with plant community similarity matrices constructed based on size distribution measurements (Oksanen et al., 2017). The most suitable subset of soil properties found after the *bioenv* analysis was further subjected to a permutation test using the *adonis* function in R to determine significance.

4.3 Results and discussion

4.3.1 Soil profile morphology and classification

Soils that are the result of a combination of materials, such as the materials deposited by dredges, undergo strong transformations during the early stages of formation, which are characterized by pedogenic processes similar to those occurring in natural soils (Séré et al., 2010). The morphological description of these so-called Technosols for both gravel and sand deposits (Table 4.1 and 4.2) shows a superimposition of sub-horizontal layers, in some cases with wavy boundaries within layers. In the gravel deposits, fine roots are rare in the C horizons. However, frequent fine and medium roots could be observed in O horizons (0-2 cm). Formation of O horizons, dominated by organic material, is observed for gravel deposits with >4 years of revegetation, and for sand deposits with >8 years of revegetation. Both types of deposits are pedologically poorly developed, as they still do not show traits of incipient pedogenesis, and structure formation is not yet observed. This means that the Technosols still retain most of the structural features of the geologic deposits from which they were formed (USDA, 1999). However, there is clear evidence of the rapid development of new horizons, visually distinguished according to color and root density in both types of deposits. This is a typical behavior of Technosols in early stages of formation as observed by Scalengue and Ferraris (2009), who state that profile development is minimal in Technosols of young age. However, the formation of O horizons in soils >4 years of revegetation evidences the development of an increasingly abundant plant cover that consequently increases the amounts of soil organic matter in topsoil with increasing age (Uzarowicz et al., 2017).

Different kinds of material are recorded in both gravel and sand deposits with >4 years of revegetation, with changes in particle-size distribution and color. The upper layers of the gravel deposits exhibit a light brown color (10 YR4/3), rounded and sub-rounded gravel, and a few fine roots in the younger gravel deposits, and abundant fine and medium roots in the gravel deposits with >8 years of revegetation. Deeper in the profile, layers with various shades of yellow could be identified (5Y6/4, 5Y7/6). Thick roots are noted in the gravel deposits with 12 years of revegetation. The upper layers of the sand deposits are of dark yellow and brown color (2.5Y 5/4, 10 YR 4/3), with fine and medium roots in areas with >4 years of revegetation. Abundant fragments of angular and sub-rounded quartz, as well as abundant coarse pores, occurred in the upper layers of the sand deposits.

Table 4.1. Morphological description of profiles of gravel deposits for each time period since revegetation.

Period	Vegetation	Horizon	Depth	Color	Structure	Consistence	Other features
0	*Pueraria phaseoloides*	C	0-50 cm	10YR 4/3 (wet), 10YR 5/4 (dry)	No structure	Non-plastic	Few fine roots. 70% gravel (diameter: 0.2-1 cm), 15% gravel (diameter: 1-2 cm), 15% rounded and sub-rounded gravel (diameter 2-10 cm)
4	*Moringa oleifera*	O	0-2 cm	10YR 2/2 (wet)	No structure, loose	Non-plastic, non-sticky	Organic matter in decomposition. Frequent fine and medium-sized roots. Abundant sub-rounded quartz grains, size of fine

Period	Vegetation	Horizon	Depth	Color	Structure	Consistence	Other features
							sand. Frequent light-colored mica, size of very fine sand. Abundant fragments of rock, size of fine and medium sand. Frequent fragments of rock (diameter: 1-5 mm).
		C	2-45 cm	5Y6/4 (wet), 5Y7/6 (dry)	Loose	Non-plastic, non-sticky consistency	Few fine roots. 60% gravel (diameter 0.5-1 cm), 30% gravel (diameter 1-4 cm), 10% gravel (diameter 4-10 cm).
8	*Musa x paradisiaca*	C	0 - 50 cm	10YR 4/4 (wet)	Loose	Non-plastic, non-sticky	Abundant fine and medium roots. Frequent fine pores. 80% stoniness, 50/50 proportion of gravel, rounded and sub-rounded gravel.
12	*Psidium guajava* *Acacia mangium*	O	0-4 cm	7.5 YR 5/3 (wet)	Loose	Non-plastic, non-sticky	Abundant fine and medium roots, few thick roots. Organic matter undergoing medium to advanced decomposition.
		C	4-40x cm		Loose		Stoniness. Loosen gravel. Few fine roots. Deposit with 80% of rounded gravel (diameter 0.5 – 4 cm), 20% rounded stoniness (diameter 4-10 cm).

Table 4.2. Morphological description of profiles of sand deposits for each year of establishment.

Year	Vegetation	Horizon	Depth	Color	Structure	Consistence	Observations
0	*Pueraria phaseoloides*	C	0-50 cm	2.5Y 5/4 (wet), 2.5Y5/2 (dry)	No structure, loose	Non-plastic, non-sticky	Abundant angular quartz fragments, size of fine and very fine sand. Frequent lithic mafic angular and sub-rounded fragments.

Year	Vegetation	Horizon	Depth	Color	Structure	Consistence	Observations
							Frequent sub-rounded quartz grains, size of very fine sand.
4	*Musa × paradisiaca* *Theobroma cacao*	C	0 - 7 cm	10YR3/4 (wet)	No structure	Slightly plastic non-sticky	Frequent fine roots. Abundant fine and medium roots. Abundant fine pores. Abundant light-colored mica, size of very fine sand. Roots with insects.
		C_2	7-15 cm	10 YR 4/3 (wet)	No structure, loose	Non-plastic, non-sticky	Coarse porosity. Abundant quartz sub-rounded fragments, size of fine sand. Abundant lithic fragments, size of fine sand. Frequent accumulation of iron oxide.
		C_{3g}	15-29 cm	60% 2.5Y5/3 (wet), 40% 10YR3/6 (wet)	Loose	Slightly firm consistency, slightly plastic and sticky	Abundant fine roots. Abundant fine pores. Frequent accumulation of iron oxide in channels. Frequent quartz grains, size of very fine sand.
		C_{4g}	29-48 cm	80% 5Y5/1 (wet), 20% 7.5YR 4/6 (wet)	Loose	Plastic and sticky	Few fine roots, abundant fine pores. Abundant accumulation of iron oxide in root channels. Frequent mica fragments, size of very fine sand. Evidence of redox processes. Porosity associated with root channels with a vertical orientation. Abundant fine root channels.
			48-x cm	90% GLEY 1 6/5 GY (wet), 10% 7.5YR 5/8 (wet)	Loose	Non-plastic, non-sticky	Abundant coarse pores. Abundant quartz grains, rounded and sub-angular, size of fine and medium sand. Abundant lithic fragments, size of medium sand. Frequent light-colored mica fragments, size of sand.
8	*Acacia mangium*	O	0-1 cm		Loose	Non-plastic, non-sticky	Sapric material. Materials undergoing an early stage of decomposition. Structure and tissue of litter are conserved.
		C	1-40x cm	2.5Y 5/3 (wet)	Loose	Non-plastic, non-sticky	Few fine and medium roots. Abundant coarse pores. Frequent quartz grain, size of very fine sand. Few fragments of light-colored mica, size of very fine sand. Frequent lithic fragments, size of very fine sand. Few fragments of quartz (diameter >2 mm).
12	*Citrus × limon*	O	0-40 cm	10YR 4/4 (wet)	Loose	Non-plastic, non-sticky	Few fine and medium roots. Abundant coarse pores.

Year	Vegetation	Horizon	Depth	Color	Structure	Consistence	Observations
		C	40-x cm	:40% 2.5Y 5/6 (wet), 60% 5Y 5/1 (wet)	Loose	Non-plastic, non-sticky	Abundant fine pores, frequent accumulation of iron oxides in root channels. Abundant sub-rounded quartz grains, size of fine sand and rounded size of medium sand. Frequent lithic mafic fragments, size of fine sand. Few lithic fragments, diameter greater than 5 mm.

Redoximorphic features (Lindbo et al., 2010) were observed in the profile of the sand deposit revegetated since 2010, where the water table was found at a depth of 58 cm. Accumulation of iron oxide in the root channels was found in sand deposits with >4 years of revegetation, suggesting temporary changes in the redox potential. In addition, the presence of sapric material was found in the sand deposit with 8 years of revegetation. Organic matter decomposition was observed in gravel deposits undergoing revegetation for >4 years and biological activity of mesofauna in the profile of sand deposits with 4 years of revegetation. In both sand and gravel deposits, the abundance and size of roots increased from younger to older revegetation areas. The presence of sapric material, as well as the biological activity after 4 years of revegetation, suggests that porosity and aggregation processes increased with time under the influence of biological factors. Therefore, the pedogenetic development of the studied Technosols can be similar to that of natural soils influenced by biological factors (Jangorzo et al., 2015).

4.3.2 Changes in soil chemical, physical and hydraulic properties along the chronosequence of revegetation

Three-way permutational analysis of variance was performed for two groups of soil properties: soil chemical properties (pH, Al, N, OM, P, K, Ca, Mg, Fe, Mn, Zn, Cu, Na), and soil physical and hydraulic properties (sand, silt, clay, bulk density, stability index, field capacity, saturated water content, permanent wilting point, saturated hydraulic conductivity). Soil chemical properties vary significantly between gravel and sand deposits (p = 0.004). In addition, there is a significant interaction between the factors soil type and year of establishment (p = 0.01). Following up on the interaction, a permutational analysis of variance for each soil type (gravel and sand deposits) was performed independently for the different time periods of vegetation establishment. Results show that for sand deposits there is no significant difference among the different time periods of vegetation reestablishment, while gravel deposits exhibit significant changes (p < 0.001).

Median values of soil properties corresponding to the different time periods since the establishment of the revegetation plots and different deposit types are shown in Table 4.3. Kruskal-Wallis test and Kruskal-Wallis multiple comparisons were conducted for each chemical property of the gravel deposits to assess significant changes among different time periods since establishment. Results show significant changes in pH, P, K, Ca, Cu and Na. Gravel deposits with >4 years of revegetation have significantly lower pH, lower P, K, Ca, Cu and Na values compared with gravel deposits that were still without vegetation cover.

Table 4.3. Median values of physicochemical properties of sand and gravel deposits corresponding to different years since the establishment of revegetation plots. Median values of gravel deposits with different letters in the rows are significantly separated ($p \leq 0.05$).

Property **Years since the establishment of revegetation**	**Gravel**				**Sand**			
	0	**4**	**8**	**12**	**0**	**4**	**8**	**12**
pH	7.05^{b}	5.4^{a}	5.1^{a}	5^{a}	5.7	5	4.5	5.6
OM (%)	6.39	8	9.21	7.64	6.06	7.89	7.36	7.36
N (%)	0.28	0.34	0.38	0.33	0.27	0.33	0.32	0.32
P (mg/kg)	17.9^{b}	7a	5a	9a	11	5.5	8	7
K (cmol(+)/kg)	0.51^{b}	0.37^{a}	0.43^{a}	0.40^{a}	0.34	0.35	0.34	0.31
Ca (cmol(+)/kg)	13.03^{b}	6.86^{a}	6.49^{a}	6.24^{a}	2.78	6.13	3.47	2.29
Mg (cmol(+)/kg)	5.32	3.12	2.8	1.78	0.88	2.92	1.58	1.55
Fe (mg/kg)	96	84	112	159	62	162	127	64
Mn (mg/kg)	29.09	98.69	70.43	78.34	61.08	86.08	55.8	62.08
Zn (mg/kg)	8.08	10.99	21.28	1.81	1.3	3.31	1.36	0.79

Cu (mg/kg)	8.69^b	3.12^a	3.71^a	4.27^a	1.03	8.48	3.16	1.62
Na (cmol(+)/kg)	0.32^b	0.19^a	0.19^a	0.12^a	0.13	0.19	0.13	0.09
Al (cmol(+)/kg)	0	0	0.8	0.8	0	0.65	0.7	0
Sand (%)	40	73	59	78	90	55	69	85
Silt (%)	24	10	13	5	4	27	23	5
Clay (%)	32	16	28	14	6	16	8	10
Bulk density (g/cm^3)	1.64	1.53	1.34	1.29	1.32	1.08	1.15	1.39
Stability index	0.07	0.09	0.4	0.28	1.93	0.19	0.55	0.67
Field capacity (%)	10.72	10.77	12.01	7.65	10.87	10.23	10.23	11.38
Saturated water content (%)	15.01	15.94	16.83	11.1	16.31	15.34	15.35	16.67
Permanent wilting point (%)	5	5.92	6.55	4.2	5.97	5.57	5.01	6.25
K_{sat} (cm/h)	5.85	0.23	7.54	0.28	0.32	0.003	0.23	0.05

K_{sat}: Saturated hydraulic conductivity

Three-way permutational analysis of variance of soil physical and hydraulic properties revealed no significant changes among deposit type, time period since establishment of vegetation or sampling depth. The relatively short time of establishment of the revegetation plots indicates that environmental conditions and climate have only had a short time to significantly influence the physical properties. Ruiz-Jaen et al. (2015) propose that significant changes in soil physical properties in post-mining landscapes can be evidenced after 15 years.

4.3.3 Comparison between gravel and sand deposits

Linear discriminant analysis (LDA) was conducted to determine which chemical properties of the soil contributed the most to differences between the different deposit types. Results show that Ca and P content contribute the most to differentiating gravel and sand deposits, and that Zn, Al, Cu, and Fe were also of considerable importance (Table 4.4).

Table 4.4. Ranking of soil chemical properties that contributed most to differentiate gravel and sand deposits based on linear discriminant analysis (LDA).

Soil property	Absolute weight	Variable rank
Ca	2.69	1
P	1.29	2
Zn	1.21	3
Al	1.11	4
Cu	1.08	5
Fe	1.05	6
Mn	0.49	7
pH	0.47	8
K	0.30	9
N	0.17	10
Mg	0.16	11
Na	0.04	12

Phosphorus levels in gravel deposits with >4 years of revegetation are significantly lower than in gravel deposits with no vegetation cover. In the context of revegetation of mine spoils, P is essential for restoring most of the biogeochemical processes. Previous studies conducted by Castellanos et al. (2010) in the same research area show that P was the nutrient that limited the productivity of the tree *Acacia mangium* used to reforest sand and gravel deposits (Castellanos and Leon, 2010). Therefore, as a consequence of vegetation reestablishment, the P concentration is reduced.

The K, Ca and Mg contents are higher in gravel deposits as well as the concentration of Zn and Cu. Metallic micronutrients are also essential for plant growth but are soluble in acidic conditions in which they can dissolve to toxic concentrations that may actually hinder plant growth (Sheoran et al., 2010). Lindsay and Norvell (1978) mention values rated as highly sufficient for ecologically sustainable reclamation as being 4.5 mg/kg Fe, 1.0 mg/kg Mn, 1 mg/kg Zn and 0.4 mg/kg Cu (Lindsay and Norvell, 1978). In the gravel deposits, in 97% of the samples, Zn exceeded the concentration recommended by the above authors, while in contrast, only 6% of the sand deposit samples had Zn concentrations above the threshold. All samples showed levels of Fe, Mn, and Cu that exceeded the threshold recommended by the authors. Critical levels of Mn that can begin to affect the yield of sensitive species are >65 mg/kg Mn (Hazelton and Murphy, 2007). For the gravel deposits, 52% of the samples had Mn contents above the critical level, and 46% of the sand deposits also showed Mn values above the critical level. The high concentration of metallic micronutrients might, therefore, be explained by the observed acidic conditions and the nature of the deposits.

For chemical soil analysis, gravel is defined as samples containing mineral particles with a diameter >2 mm. Gravel is usually considered to have no effect on the chemical and biological functioning of the soil and is removed before the laboratory analysis. Overall, the analysis of the chemical properties suggests that gravel deposits have a higher nutrient and organic matter (OM) content. However, the gravel content represented 8.4 ± 3.7% (SD) of the total weight of the samples. Therefore, the nutrient stock can be overestimated (Rytter, 2012). Even if gravel is considered as an inert component of a soil, it has a diluting effect on the amount of stored water and nutrients, affects infiltration and runoff rates, and introduces heterogeneity into soils. This can have either positive or negative effects on crop production. One of the positive effects of gravel is that it decreases the soil buffering power. Therefore, fertilizer applications may be more effective than on gravel-free soils (Bowden, 2013). Fertilizer recommendations and management strategies for gravel deposits should consider gravel content as well as bulk density and should be adjusted to a whole soil basis.

Moreover, the high N and OM contents of both deposit types could be explained, because the actual deposits were former bottoms of sedimentation basins (Shlyakhov and Osipov, 2004). Therefore, the material was deposited in a mixed manner with OM-rich layers that might compensate the lack of macronutrients of OM-poor layers (Meuser, 2013). The analysis of bulk density in the context of deposit revegetation is crucial, given that high bulk densities might limit rooting depth. Severely compacted soils (bulk density > 1.7 g/cm^3) cannot hold enough plant-available water to sustain plants during dry seasons (Maiti and Ghose, 2005). In addition, it is expected that while reclaiming mining land, the soil becomes compacted with the consequent overall decrease in groundwater recharge (Ahirwal and Maiti, 2016). For the study site, the bulk density values cannot be considered as those of severely compacted soils, although the gravel deposits had higher bulk densities than the sand deposits (Table 4.3). Furthermore, the volumetric field capacity for both deposits was below 20%. This parameter did not exhibit significant changes across the reconstructed chronosequence, which is also related to the weak structure observed for these deposits. On the same lines, very rapid infiltration was observed for both types of deposits, as well as high saturated hydraulic conductivities.

4.3.4 Plant community succession

The most abundant tree species in the sampling plots undergoing revegetation were *Cecropia peltata* (Urticaceae), *Acacia mangium* (Fabaceae), *Vernonanthura patens* (Asteraceae) as well as shrubs such as *Eupatorium vitalbae* (Asteraceae), *Rubus ulmifolius* (Rosaceae), and *Calathea lutea* (Marantaceae) (Table 4.5). Height distribution of the vegetation was calculated for trees and shrubs in different years of establishment of revegetation for both deposit types (Figure 4.2). Profiles show that smaller trees <5 m in height predominated on the plots with >4 years of vegetation reestablishment. A few taller trees (> 10 m height) were found with <4 years of revegetation, and were more abundant in areas with >8 years of revegetation. The height profiles also reveal that the count of live trees in each height range is higher for gravel than for sand deposits.

Table 4.5. Abundant species found in the revegetation area.

Growth form	Species
Herbaceous	*Calathea lutea* (Marantaceae)
	Cyperus ferax (Cyperaceae)
Shrubs	*Eupatorium vitalbae* (Asteraceae)
	Heterocondylus vitalbae (Asteraceae)
	Rubus ulmifolius (Rosaceae)
	Acacia mangium (Fabaceae)
Trees	*Cecropia peltata* (Urticaceae)
	Guazuma ulmifolia (Malvaceae)
	Miconia minutiflora (Melastomataceae)
	Sapium glandulosum (Euphorbiaceae)
	Tectona grandis (Lamiaceae)
	Vernonanthura patens (Asteraceae)

For shrubs, the height distribution reveals similar counts of individuals among the different height ranges for deposits with 4 years of revegetation. However, gravel deposits with >8 years had higher counts in all height ranges. Analysis of similarity based on the Bray-Curtis index shows that the time period since revegetation had a higher effect (R = 0.27, p = 0.001) on changes in size distribution (diameter and height) of trees than the deposit type (R = 0.04, p = 0.001). However, for height distribution of shrubs, it was observed that time period since establishment had a similar effect (R = 0.19, p = 0.001) to that of deposit type (R = 0.19, p = 0.001).

Analysis of plant density of trees and shrubs in terms of live individuals per square meter (Table 4.6) shows significant changes in plant density of trees, with significantly higher values (p = 0.01) for areas with >4 years of revegetation. No significant differences are observed for shrubs among the different time periods since revegetation nor between gravel and sand deposits. Analysis of vegetation development through the calculation of size profiles based on the size structure of the vegetation in four different areas with different time periods since revegetation provides evidence of a progressive vegetation succession. In the specific case of Technosols, a progressive plant community succession is only achievable through a favorable combination of soil type, soil physical regime and type of primary plant community (Ciarkowska et al., 2016).

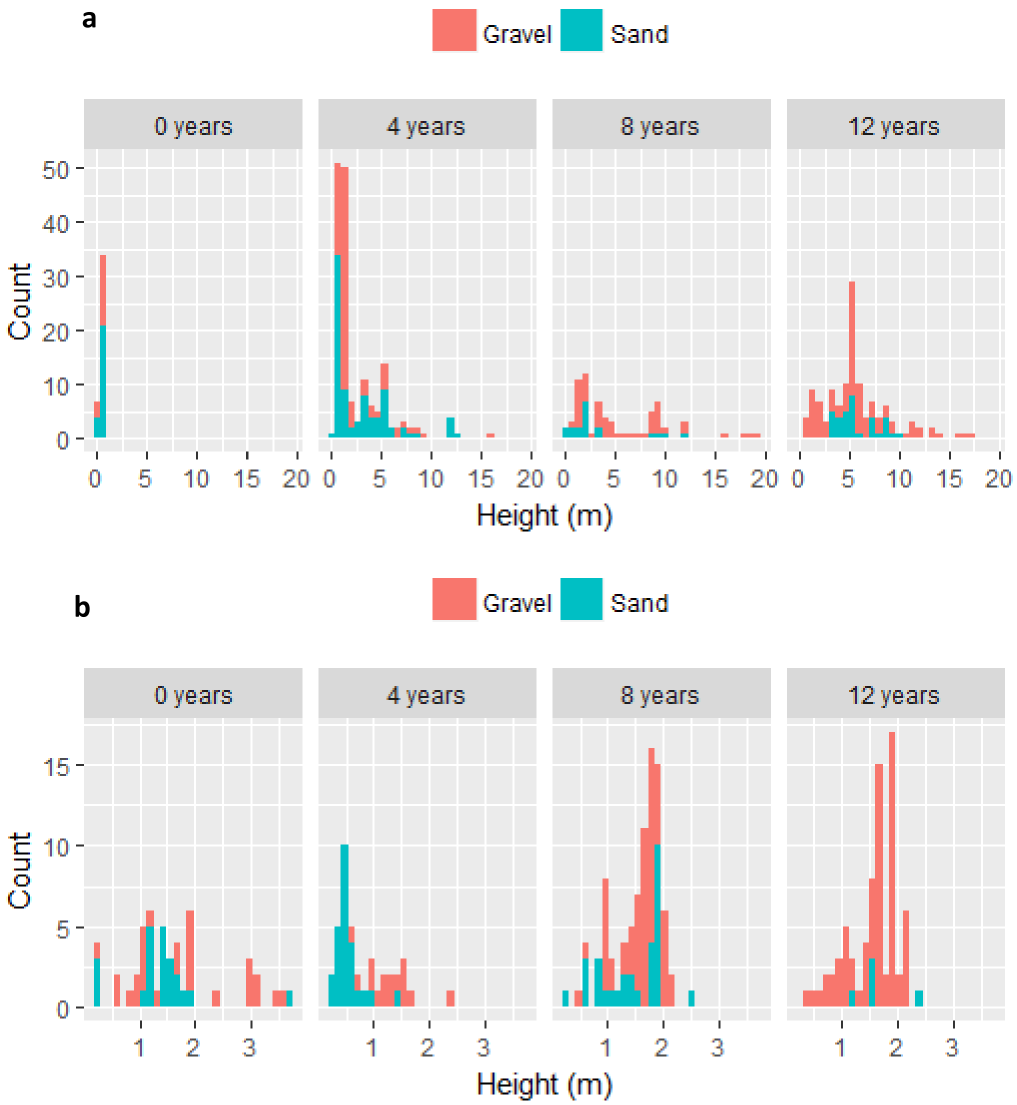

Figure 4.2. Abundance profiles of (a) trees and (b) shrubs calculated for different years of establishment of revegetation plots for gravel and sand deposits using total height as a structural variable.

The fact that trees and shrubs were taller in the gravel deposits suggests that the plant roots proliferated in the nutrient-rich zones of these deposits. This can be due to the high nutrient content of the 2-mm fraction of the gravel deposits and the observed uneven distribution of this fraction within the deposit layers. Plants can respond morphologically to heterogeneity in nutrient availability by preferentially growing roots in nutrient-rich zones or by shifting growth allocation to or from roots (Robinson, 2005). Therefore, changes in root architecture can be mediating adaptation of the plants to these deposits (López-Bucio et al., 2003).

Table 4.6. Mean values of plant density (plant/m^2) (N = 24) for trees and shrubs in sand and gravel deposits corresponding to different time periods since establishment of revegetation plots. Mean values of tree density in plots located in gravel deposits with different letters in the rows are significantly separated ($p \leq 0.05$).

Time period	**Gravel**		**Sand**	
	Trees	**Shrubs**	**Trees**	**Shrubs**
0 years	0.05^a	0.09	0.08	0.07
4 years	0.27^b	0.05	0.28	0.08
8 years	0.16^b	0.19	0.06	0.10
12 years	0.30^b	0.23	0.13	0.02

4.3.5 Relation of Technosol properties with variation of size structure of plant community

Linking the size structure of the plant community to the variations of the chemical properties of the Technosol (Table 4.7) shows that pH, P and Mg have a stronger influence on plant growth compared to the other chemical properties. Previous research conducted on Technosols of bauxite residue shows that nutrient availability and physicochemical fertility depend mostly on the formation of aggregates (Vidal-Beaudet et al., 2016). The structural stability of the gravel deposits is much lower than that of sand deposits, therefore a careful selection of the plant species to be used in these areas is required. For example, the use of legumes can increase soil-N content, increase organic matter as well as improve soil porosity and structure (Li et al., 2016). In addition, grasses characterized by fast growth can also help to stabilize the substrate and cover the land, and therefore can be used as a suitable initial cover for the barren deposits (Fullen et al., 2006). Vegetation succession will change the dominant plant cover of recently formed deposits from grasses to trees and shrubs, which will likely aid structure development through root binding (Santini and Fey, 2016). Therefore, understanding the pedogenesis of Technosols is essential to designing sustainable revegetation techniques, especially when the soil is to be used for agricultural purposes.

Table 4.7. Set of soil properties that best correlate with dissimilarities of community size structure. Results of permutational analysis demonstrate the significance of each parameter.

Set of soil properties	Spearman correlation	p-value
pH + P + Mg	0. 4365	pH (0.034) P (0.023) Mg (0.039)

Post-mining Technosols are often considered to be unfavorable for agricultural use and vulnerable to erosion (Kołodziej et al., 2017). However, the farmers living in the study area have the challenge to identify management strategies and areas where crop yield is not significantly affected by the quality of the substrate. The fact that sand and gravel deposits have remarkably different properties also suggests that for crop establishment they should be managed differently. Consequently, soil surveys are required to characterize the nutritional and physical properties of the deposits to develop management strategies for agricultural use and reforestation. In addition, crop selection should take into account the different properties of the deposits. Limiting factors for revegetation of sand deposits are low contents of P and exchangeable cations, and high Fe, Mn, Zn and Al contents. Limiting factors for revegetation of gravel deposits are those mentioned for sand deposits in addition to a very poor structural stability.

Some unfavorable soil properties can be compensated for through the application of special ameliorative measures and the adoption of crop growing technologies, yet it is difficult to compensate limiting factors such as soil texture, stoniness and gravel content. However, studies on soil suitability for growing fruit trees show that large orchards can be established in areas considered to be of limited suitability for crop establishment and horticulture (Savin et al., 2016). Therefore, the establishment of orchards can be a suitable option for revegetation of gravel deposits. Furthermore, the choice of tree species for revegetation should be related to their capacity to increase soil nutrients and sequester soil organic carbon. Therefore, the exclusive establishment of fast-growing trees may not be as beneficial as the plantation of mixed stands (Neina et al., 2017). For crop production, sand deposits could be used, but organic amendments would be required for growth and maintenance of the crops. Initial coverage with natural topsoil might favor the establishment of soil ecosystem engineers such as earthworms and ants, and can play a decisive role in the development of plant communities. Furthermore, to enhance the structure and properties of the Technosols, amendments such as green waste or composts can be applied (Vergnes et al., 2017). In acidic areas with low concentrations of cation exchange, liming or especially wood ash application would be a suitable strategy due to the neutralizing capacity and availability in most households in the area (Neina et al., 2017). In areas with high bioavailable concentrations of Zn, Mn, Cu and Fe, species such as *Brachiaria decumbens* or *Lolium perenne* could be planted given their high tolerance to low fertility and high capacity to reduce the mobility of these metals in the soil. In addition to phytostabilization, plant-growth promoting bacteria could be applied to improve the tolerance and growth of these plants on soils with high metal concentrations (Rodríguez-Seijo et al., 2014).

4.4 Conclusions

The variability of the studied Technosols is primarily influenced by the type of deposit formed, i.e. gravel or sand deposit. It depends on the technology used for alluvial gold mining such as bucket dredges that create gravel deposits or suction dredges that create sand deposits. The physical and hydraulic properties of both deposits are rather similar, however, their chemical properties vary. Gravel deposits have higher nutrient contents in the fine fraction, therefore, the diluting effect of the rocks and pebbles of these deposits should be considered in the design of management strategies and fertilizer recommendations. Sand deposits have better structural properties than the gravel deposits, therefore an adequate revegetation scheme with fast-growing plants could promote an overall improvement in the physicochemical fertility of these deposits.

The vegetation cover on gravel deposits is developing faster than that on sand deposits, which could be due to the higher nutrient contents of the fine fraction in the gravel deposits combined with the adaptation of plant-root architecture for reaching the nutrient-rich zones of these deposits. Therefore, plant selection for revegetation of gravel deposits should also take into account the capacity of the plants to increase the efficiency of nutrient capture in nutrient-poor zones of these deposits. Moreover, as gravel deposits sustain a greater vegetation cover, there is evidence of a decrease in nutrient levels in older revegetation areas. Given the great importance of P for vegetation reestablishment, a suitable fertilization scheme should be designed to guarantee sufficient P availability for sustained vegetation growth.

The Technosols formed after alluvial gold mining activities exhibit nutrient contents and structural properties that make them suitable for agricultural use. However, selection of crops and trees for revegetation should consider the high concentrations of metallic micronutrients that can be potentially toxic to the plants. These deposits can ensure essential functions for rural areas such as woody biomass production and crop establishment if gravel deposits and sand deposits are managed differently and specific crop selection for each deposit is done based on its respective properties.

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5. DELINEATION OF HOMOGENEOUS ZONES IN SITES COVERED BY GOLD MINING WASTE UNDERGOING RESTORATION WITH AGROFORESTRY SYSTEMS

Abstract

Alluvial gold mining activities generate large amounts of dredged sediments that are deposited on the banks of and in areas near rivers. Agroforestry systems have been established for reclamation of these deposits in the gold mining area of El Bagre, Colombia, with the aim to support agricultural land use by establishing crops in more fertile areas of the deposits while making non-fertile areas productive through the planting of trees. Spatial variability of these sediment deposits depends on the type of machinery used for mining and the geochemical properties of the exploited alluvial areas.

To support farmer's decision making regarding soil management, the main objective of this study is to understand the patterns of spatial variability of the soil properties of the deposit areas that might affect plant growth and crop productivity. For this purpose, homogeneous zones were delineated to identify areas with homogeneous properties within farmers' fields, i.e. areas within a field with similar characteristics such as texture and nutrient levels. Soil samples were taken from 310 locations distributed in four reclamation areas of 50 ha each established in 2014, 2010, 2006 and 2002. Maps of the soil properties were generated through spatial interpolation with ordinary kriging. Spatial principal component analysis and fuzzy cluster classification were performed to delineate the homogeneous zones. For validation, multispectral aerial images were used to create maps of vegetation indices, and integrate these with field measurements of physicochemical soil properties.

5.1 Introduction

Alluvial gold mining activities generate large volumes of dredged rocks and sediments that destroy riparian ecosystems, cover large areas previously dedicated to agriculture or other land uses, and thus severely change the pedological properties (Shlyakhov and Osipov, 2004). In undisturbed soils, spatial and temporal variability is a result of the dynamic interaction of natural processes and management practices (Buttafuoco et al., 2010; Panakoulia et al., 2017) . In the case of deposits of dredged rocks and sediments generated by mining activities, variability is not only determined by these factors but also depends on the type of machinery used for mining, as well as on the geology and geochemical properties of the parent material (Shlyakhov and Osipov, 2004). Moreover, the nature of the substrate that forms these deposits makes colonization by plants difficult. The texture can be very coarse in rock wastes, intermediate in sand wastes, or very fine in milled tailings. These deposits usually have low macronutrient levels and a low pH (Cooke and Johnson, 2002). There is also a discontinuity between the upper and lower layers of the soil profile due to the superposition of the mine waste over the natural soil (Bini and Bech, 2014).

When farmers attempt to use these severely disturbed lands for agriculture, they have to deal with several crop-limiting factors such as water and nutrient availability (Córdoba et al., 2016). One of the main challenges they face is to identify areas suitable for crop establishment in which productivity is not reduced by such crop-limiting factors. For this reason, in areas undergoing reclamation through agroforestry, understanding the spatial variability of soil properties that affect growth and productivity is crucial.

The delineation of homogeneous zones can be a useful method to understand variability within a farmer’s field (Gertsis et al., 2015). These zones are areas within a field with homogeneous characteristics such as texture, topography and nutrient levels (Schemberger et al., 2017). Even though an accurate definition of homogeneous zones can be difficult due to the complex interactions of factors that could affect crop establishment and yield (Moral et al., 2010), understanding spatial variability of the soil can support the development of an effective management strategy to restore the productivity of the heavily degraded lands. The delineation of homogeneous zones requires detailed information to characterize the within-field variability of soil properties, plant and crop yield (Sona et al., 2016). Multivariate geostatistics is a tool widely used to subdivide a field into smaller and more homogeneous units through the analysis of spatial relationships of variables, i.e. soil physical, chemical and biological properties (Buttafuoco et al., 2015). Furthermore, data from optical sensors can be combined with the analysis of these properties to characterize variability and improve the delineation of homogeneous zones (López-Lozano et al., 2010; Pinheiro et al., 2017).

Recent advancements in the use of multispectral cameras mounted on drones for agricultural management provide an efficient way of collecting high-resolution data in areas where satellite images have poor spatial or temporal resolution (Sona et al., 2016). Multispectral images of vegetation cover are combined to obtain vegetation indices. Here the Normalised difference vegetation index (NDVI) is a good estimator of productivity and is commonly used for this purpose given its high correlation with leaf chlorophyll, green biomass and leaf area index (LAI) (Cicore et al., 2016). NDVI maps can be used as effective measures of vegetation activity and are useful parameters to characterize differences in crop canopy characteristics, as well as to assess spatial variability of agricultural fields (Al-Gaadi et al., 2014). Furthermore, NDVI is considered as one of the most important vegetation indices for the prediction of crop production due to it its strong relationship with crop yield (Mkhabela et al., 2011; Wall et al., 2008).

To support farmers’ decision making regarding soil management of areas undergoing revegetation with agroforestry systems, the main objective of this study is (i) to understand the spatial variability of the soil properties of the deposit areas that might affect plant growth and crop productivity, (ii) to investigate the spatial correlation between NDVI and the analyzed soil properties, and (iii) to delineate and validate homogeneous zones within the areas undergoing restoration. These objectives aim to support the design of specific management schemes for each zone to maximize the overall production potential of the farms by addressing specific agronomic requirements for both crop production and vegetation establishment.

5.2 Methodology

5.2.1 Study area

The study was conducted in north-west Colombia in the gold mining area of El Bagre, Antioquia (Figure 5.1). The area lies in a humid tropical forest zone (Espinal, 1992) with an average temperature of 28°C and a mean precipitation is 2.000 - 4.000 mm. The region has a dry season from November to March and a rainy season from April to October. The topography of the area is mostly flat. The low-lying forest remains flooded most of the year, preventing productive agriculture, animal husbandry or forestry. These areas are the most affected by the gold mining activities of the company Mineros S.A.

Areas to be restored are flattened with heavy machinery to reduce the slope below 30% for the subsequent establishment of a vegetation cover. The restoration efforts of the mining company focus on gravel and sand deposits. From the total area that needs to be restored, depending on location and stability of the deposits, specific areas are selected to implement agroforestry systems. The parcels are allocated to farmers that meet the requirements of the company, and partnership agreements are made. Resources for crop establishment as well as a subsidy are provided by the company to allow the farmers to initiate the restoration process.

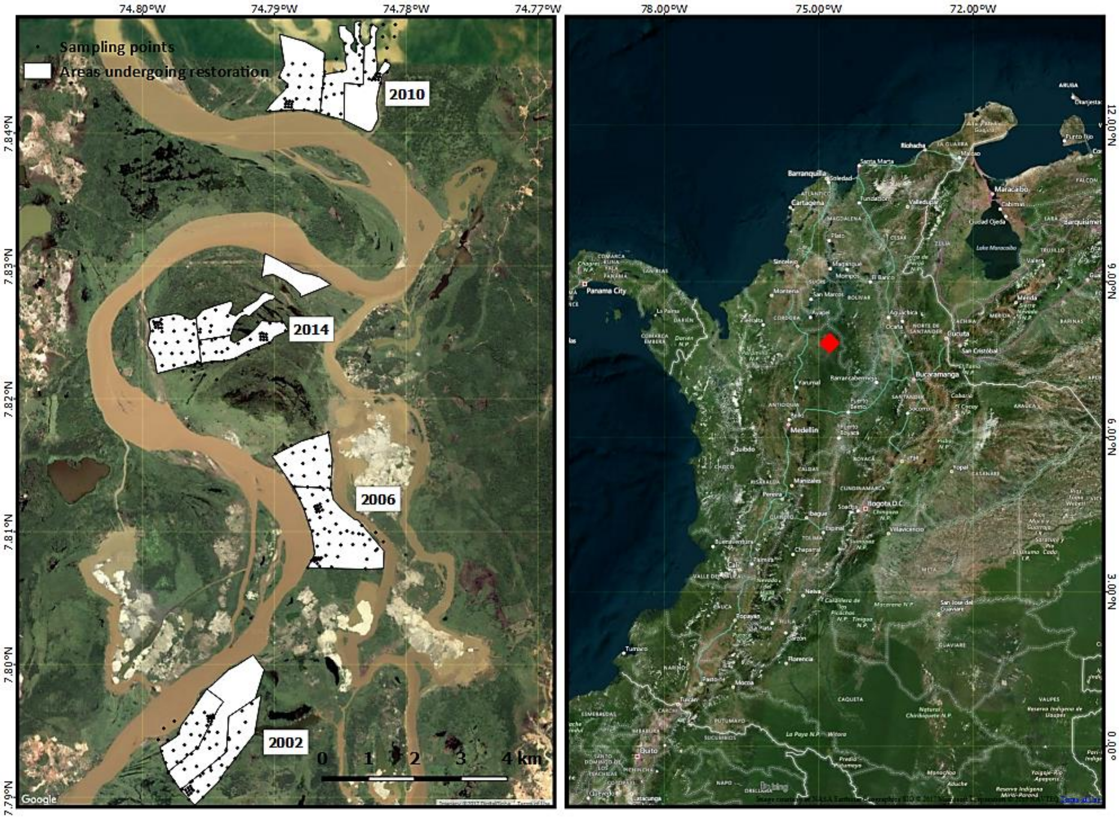

Figure 5.1. Study area**.** The map on the left shows the four restoration areas selected for this study and the soil sampling points.

5.2.2 Soil sampling and analysis

Soil samples were collected from areas undergoing restoration through the establishment of agroforestry systems from September 2015 to March 2016. Four plots established in 2002, 2006, 2010 and 2014 were selected for soil sampling and aerial photography. A regular sampling grid consisting of 312 points spaced 100 m apart (78 sampling points for each area) for the four study plots was created. In addition, one cell of the grid was randomly selected for soil sampling at 25-m spacing. For soil sampling, an auger with 10 cm diameter was used for sand deposits and a shovel for gravel deposits. Soil samples were passed through a 2-mm sieve and air dried for subsequent analysis. They were analyzed according to the Soil Survey Investigations Report No. 42 5.0 (USDA, 2014). Soil pH was determined by the potentiometric method 1:1 water. Organic matter was determined by the Walkey-Black method. Nitrogen was determined by the Kjeldahl method. Available P was determined by a modified Bray-II method.

Potassium, Ca, Mg, and Al were determined by atomic absorption spectroscopy. Soil physical analyses were performed using methodologies developed by Pla (2010). Soil texture was determined by the Bouyoucos hydrometer method. Samples for bulk density were taken using intact soil cores from each sampled surface layer. Bulk density was determined by oven-drying the cores at 105°C for 48 hours (Pla, 2010). Penetration resistance was measured with a penetrograph standard set for measurements to a depth of 80 cm (Eijkelkamp, Netherlands). Altitude, longitude and latitude were determined using a portable GPS (Garmin eTrex 10, Germany).

5.2.3 Aerial imagery

The commercially available Sensefly eBee drone was used for collection of aerial imagery (Sensefly, Chaseaux-Lausanne, Switzerland). A Parrot Sequoia multispectral sensor was adapted to the eBee for image collection (Parrot SA, USA). The sensor captured images corresponding to four separate bands: red (660 BP 40), green (550 BP 40), red edge (735 BP 10) and near-infrared (790 BP 40).The drone was flown at a minimum height of 107 m and a maximum height of 143 m obtaining an image resolution of 10-14 cm per pixel. The flight plans were programmed and monitored using eMotion2 software (Sensefly, Cheseaux-Lausanne, Switzerland), and post-flight image processing was completed using Pix4D (Pix4D SA, Lausanne, Switzerland). The eMotion 2 software uses publicly available digital elevation data from Google Earth to develop flight plans. Previews of aerial photographs and digital surface models were generated in real time, however, full data processing took several hours. The drone was flown at a default speed of 15 m/s that changed according to wind direction and speed. The average area covered by a single flight was 60 ha with an image overlap of 60 - 70%. Flights were conducted in November 2016. The resulting aerial images were overlaid with GPS data obtained by soil sampling and vegetation surveys.

5.2.4 Data analysis

Geostatistical analysis of soil properties

The geostatistical analysis for spatial interpolation was performed for the following soil properties: pH, organic matter, N, P, K, Ca, Mg, sand content, silt content, clay content, bulk density and penetration resistance measured at a 5-cm depth. Extreme values were identified graphically using box plots for each soil property and were removed from the dataset for subsequent analysis. Then a spatial data frame was created for soil properties at each sampled coordinate (Pebesma and Bivand, 2005; Bivand et al., 2013b). GPS coordinates were projected onto WGS 84 / UTM zone 18N to express distances in absolute measurements (m).

Local indicators of spatial association allow for the decomposition of global indicators, such as Moran’s I, into the contribution of each observation. The local indicators serve two purposes: (i) they may be interpreted as indicators of local pockets of nonstationarity, or (ii) they can be used to assess the influence of individual locations on the magnitude of the global statistic and to identify “outliers,” as in Anselin’s Moran scatterplot (1993). In exploratory spatial data analysis, the predominant approach to assess the degree of spatial association still ignores this potential instability, as it is based on global statistics such as Moran’s I. A focus on local patterns of association and an allowance for local instabilities in overall spatial association has only been suggested as a more appropriate perspective (Anselin, 1993). The neighborhood for each observation is formalized by means of spatial weights or contiguity matrix. The columns with nonzero elements in a given row of this matrix indicate the relevant neighbors for the observation (Anselin, 1995). Creating spatial weights is then a necessary step in using areal data to confirm that there is no remaining spatial patterning in residuals. The first step is to define which relationships between observations are to be given a non-zero weight that is to choose the neighbor criterion to be used; the second is to assign weights to the identified neighbor links (Bivand et al., 2013a). The construction of spatial neighbors and weights is discussed by Cressie (1993). A spatial weights matrix was defined for spatial autocorrelation analysis. The matrix was created using the k-nearest neighbor's methodology with the *knearneigh* function of the R package *spdep* (Bivand et al., 2013a; Bivand and Piras, 2015).

Moran and Geary's C tests were performed to detect spatial autocorrelation using the *moran.test* and *geary.test* functions. In addition, Moran's coefficient was calculated on distance classes from the set of spatial coordinates and corresponding values of each soil property to examine patterns of spatial autocorrelation. The correlogram was calculated using the *correlog* function of the R package *pgirmess* (Giraudoux, 2017). To detect influential points with significant local autocorrelation, Moran scatter plots were elaborated for each soil property, and the statistical significance of each observation was obtained using the local spatial statistic Moran's *I* calculated for each zone based on the spatial weights object. The scatter plots were elaborated using the *moran.plot* function of the R package *spdep*. Local Moran's *I* was calculated using the *localmoran* function of the R package *spdep.* Influential points generating spatial autocorrelation were detected and removed from the database for further geostatistical analysis.

There are several geostatistical approaches to estimate confidence intervals of variables in locations that have not been sampled, such as simple kriging with varying local means, kriging with an external drift, collocated co-kriging, among others (Bivand et al., 2013b). However, the results obtained with these procedures might be unsatisfactory due to the incorrect specification of the assumed parametric model. In traditional geostatistical approaches, the use of the residuals introduces a bias in the estimation of the spatial dependence and may produce a strong underestimation of the small-scale variability of the process. Even if the effect of bias may be small for kriging, in this study a bias-corrected estimator of the variograms was calculated under a complete nonparametric model, as more accurate results could be produced (Fernández-Casal et al., 2014), especially considering that the large-scale variation of these deposits cannot be assumed constant and that small-scale variation can be high.

Furthermore, discretization of the data, in this case, was not a suitable option, as it produces a loss of valuable information that was crucial to understanding the heterogeneity of these deposits. Therefore, for this study, modeling of spatial correlation was conducted following a general nonparametric procedure. Semivariograms for each soil property were calculated using local polynomial kernel smoothing of linearly binned semivariances (Fernández-Casal et al., 2014) using the *np.svar* function of the R package *npsp* (Fernandez-Casal, 2016). Maximum likelihood estimation of the parameters of the theoretical variogram was done for the following parameters: nugget variance (τ^2), partial sill (σ^2), practical range (φ), anisotropy angle (ψ_A), and anisotropy ratio (ψ_R). The nugget to sill ratio (NSR) was calculated to define different classes of spatial dependence. If the ratio is lower than 25%, the variable is considered to be strongly spatially dependent, if it is in the range 25-75%, the variable is considered moderately spatially dependent, and if the ratio is higher than 75%, the variable is considered weakly spatially dependent (Zimmermann et al., 2008). This estimation was done using the *likfit* function of the R package *geoR* (Ribeiro and Diggle, 2001). Cross-validation was performed by comparing observed and predicted values by kriging using the *xvalid* function. The performance statistics of the crossed validation were assessed in terms of mean error (ME), mean standard error (MSE), and root mean square error (RMSE). Ordinary kriging was performed for spatial interpolation of each soil property after creating a prediction grid within the borders of the study area.

Computation of vegetation indices and spatial regression with soil properties as explanatory variables

Orthomosaics elaborated with the aerial images captured with the multispectral sensor were used to calculate the normalized difference vegetation index (NDVI) using the four reflectance bands, i.e. green (550 BP 40), red (660 BP 40), red edge (735 BP 10), and near-infrared (790 BP 40). The NDVI was calculated for the four areas undergoing restoration since 2014, 2010, 2006 and 2002, and in this study is used as a proxy of plant vigor and productivity (Pettorelli et al., 2006). The NDVI maps were overlaid on soil physicochemical maps in order to visualize their impact on the spatial variability of vegetation vigor. A spatial error model (Anselin, 2013) was used to examine the relationship between the NDVI as a dependent variable and soil physicochemical properties as explanatory variables. A compact way to express this model is presented by (Bivand and Piras, 2015):

$$y = Z\delta + u \tag{1}$$

where $Z = [Y, X, Wy]$ is the set of all explanatory variables and $\delta = \left[\pi^T, \beta^T, \rho_{Lag}\right]^T$ is the corresponding vector of parameters. The error vector u follows a spatial autoregressive process of the form:

$$u = \rho_{Err} Mu + \varepsilon \tag{2}$$

ρ_{Lag} is the spatial autoregressive parameter on the spatially lagged dependent variable y, and ρ_{Err} for the spatial autoregressive parameter on the spatially lagged residuals. π and β are corresponding parameters for endogenous and exogenous variables, respectively. M is an $n \times n$ spatial weighting matrix and Mu is an $n \times 1$ vector of observation on the spatially lagged vector of residuals. The spatial error model is formed as a special case with $\rho_{Lag} = 0$ and no endogenous variables, therefore $\pi = 0$. The assumption on which the maximum likelihood estimation of the regression coefficients relies is that $\varepsilon \sim N(0, \sigma^2)$. A maximum likelihood estimation of the model was performed using the *errorsarlm* function of the R package *spdep* (Bivand and Piras, 2015; Bivand et al., 2013a). Spatial autocorrelation of the residuals of the model was tested through the Moran I statistic to assess the validity of p-values and regression coefficients (Bivand et al., 2013b).

Delineation of homogeneous zones based on soil properties

Delineation of homogeneous zones was performed following the protocol developed by Córdoba et al. (2016) with some adaptations for this specific study. For multivariate site classification, a database of predicted soil properties was created. Data were standardized in order to transform them to comparable scales. Principal component analysis was performed on the predicted soil properties using the *dudi.pca* function of the R package *ade4* (Chessel et al., 2004). Subsequently, a multivariate spatial correlation analysis of the principal components was performed as an extension of the univariate method of spatial autocorrelation. By accounting for the spatial dependence of data observations and their multivariate covariance simultaneously, complex interactions among many variables in a spatial context can be analyzed. Using a methodological scheme borrowed from the techniques of principal components analysis (PCA) and factor analysis, a strategy for the exploratory analysis of spatial pattern in the multivariate domain was developed by Wartenberg (1985). A multivariate spatial correlation analysis of the principal components was performed using the function *multispati*.

A fuzzy *c*-means cluster analysis was performed to generate fuzzy partitions and prototypes for the spatial principal component obtained from the multivariate spatial correlation analysis. These partitions are useful for corroborating known substructures or suggesting substructure in unexplored data. The clustering criterion used to aggregate subsets is a generalized least-squares objective function (Bezdek, 1984).

A fuzzy *c*-means cluster analysis was performed on the spatial principal component obtained from the multivariate spatial correlation analysis using the *cmeans* function of the R package *e1071* (Meyer, 2017). A value for the number of clusters (*c*) is known a priori on physical grounds. If *c* is unknown, then the determination of an optimal *c* becomes an important issue. This question is sometimes termed the "cluster validity" problem. In addition to the clustering, it is essential to perform *a posteriori* measures of cluster validity (or "goodness of fit") (Bezdek, 1984). To calculate the optimal number of clusters, the following indices were calculated: Xie-Beni (XB) (Xie and Beni, 1991), Fukuyama-Sugeno (FS) (Kwon, 1998), partition coefficient (PC), and partition entropy (PE) (Tang et al., 2005). A summarizing index (SI) proposed by (Galarza et al. 2013) was used to summarize the results of the indices as shown in equation (3):

$$SI = \sqrt{XB^2 + PE^2 + PC^{-2}} \qquad (3)$$

For the validation of the delineated homogeneous zones, vegetation indices were extracted from the maps, and descriptive statistics were applied to the extracted values. Analysis of variance was performed to test differences among the values for each homogeneous zone. For calculation of the maps of vegetation indices and extraction of values, the R packages *rgdal, raster* and *rgeos* were used.

5.3 Results and discussion

5.3.1 Exploratory data analysis

The first step of the geostatistical analysis was an exploratory data analysis in which descriptive statistics were used (Table 5.1). The sandy fraction was predominant, with an average value of 68%, while silt and clay constituted 18% and 14%, respectively. Coefficients of variation for silt and clay were much higher than for sand. The soil was slightly acidic with a mean pH value of 5.09; this parameter also exhibited the lowest coefficient of variation and Al the highest. Nitrogen and OM values were high with 0.25% and 5.95%, respectively, and those of P moderate with an average 15 mg/kg. The levels of exchangeable cations were low for Na, K and Ca with mean values of 0.22, 0.18 and 2.92 cmol(+)/kg, respectively. Magnesium levels were moderate with an average 1.36 cmol(+)/kg. Bulk density was relatively low (0.91 g/cm^3), which reveals that there was no severe compaction that could inhibit root penetration. However, average penetration resistance values of 1.93 MPa suggest that the soil has a dense consolidation, therefore cereal root growth could be restricted. For all soil properties, mean and median values were quite similar; however, skewness values were high for most of the parameters, with the exception of pH that was the only normally distributed parameter. Outliers were scarce and were removed after identification through box plots for each soil property. The values for pH, N, bulk density, moisture and penetration resistance were fairly symmetrical in contrast to textural parameters such as sand (skewness = -1.18) and clay (skewness = 2.10), which were highly skewed.

Table 5.1. Descriptive statistics of soil properties in the study area.

Variable	Mean	Median	SD	Min	Max	CV	Skewness	Kurtosis
				2014				
pH	5.41	5.3	0.51	4.2	6.7	0.09	0.25	0.03
N (%)	0.36	0.31	0.12	0.27	0.69	0.33	1.52	1
OM (%)	9.06	7.11	3.87	6.02	18.7	0.42	1.57	1.1
P (mg/kg)	12.24	13	7.12	0	44	0.58	0.88	3.58
K (cmol(+)/kg)	0.12	0.09	0.09	0.02	0.53	0.83	1.61	3.78
Ca (cmol(+)/kg)	2.78	2.46	2.25	0.28	9.1	0.81	1.31	1.1
Mg (cmol(+)/kg)	0.98	0.37	1.09	0.14	4.6	1.11	1.68	2.07
Na (cmol(+)/kg)	0.26	0.19	0.18	0.06	0.65	0.7	0.94	-0.29
Sand (%)	74	90	26.19	13	98	0.35	-1.08	-0.39
Silt (%)	14	4	18.34	0	60	1.25	1.27	0.14
Clay (%)	11	7.5	10.27	0	43	0.94	1.37	1.08
BD (g/cm^3)	1.01	0.96	0.24	0.62	1.46	0.24	0.48	-0.84
PR (MPa)	1.64	1.57	1.02	0.1	4.5	0.62	1.23	1.55
				2010				
pH	5.08	5.1	0.53	3.9	6.6	0.1	-0.11	-0.19
N (%)	0.22	0.2	0.16	0.01	0.71	0.75	0.73	-0.16
OM (%)	5.2	4.22	4.55	0	18.7	0.87	0.93	0.25
P (mg/kg)	15.25	16	7.78	0	34	0.51	0.035	-0.45
K (cmol(+)/kg)	0.21	0.2	0.12	0.03	0.53	0.55	0.83	0.22
Ca (cmol(+)/kg)	3.51	3.16	2.44	0.32	9.1	0.69	0.62	-0.53
Mg (cmol(+)/kg)	1.55	1.68	1.03	0	4.03	0.66	0.07	-1.21
Na (cmol(+)/kg)	0.26	0.27	0.14	0	0.65	0.56	0.15	-0.35
Sand (%)	58	54	27.4	15	99	0.47	0.02	-1.43
Silt (%)	23	24	16.98	0	69	0.72	0.35	-0.74
Clay (%)	18	16	14.84	1	60	0.81	0.99	0.27
BD (g/cm^3)	0.86	0.86	0.17	0.35	1.39	0.21	-0.08	1.51
PR (MPa)	1.42	1.05	1.03	0.1	4.5	0.72	1.53	1.68
				2006				
pH	4.98	5	0.516	4	6.2	0.1	0.05	-0.49
N (%)	0.18	0.16	0.12	0.03	0.47	0.64	0.42	-0.97
OM (%)	4.1	3.35	3.04	0.27	12.12	0.74	0.57	-0.7
P (mg/kg)	21.1	18	12.25	0	44	0.58	0.41	-0.81
K (cmol(+)/kg)	0.19	0.2	0.12	0	0.53	0.62	0.97	1.04
Ca (cmol(+)/kg)	2.59	2.48	1.49	0.34	6.78	0.57	0.74	0.42
Mg (cmol(+)/kg)	1.21	1	0.88	0.21	4.6	0.73	1.49	2.33
Na (cmol(+)/kg)	0.15	0.15	0.09	0.04	0.65	0.63	2.14	7.34
Sand (%)	71	78	22.68	18	99	0.32	-0.57	-0.91
Silt (%)	17	12	15.79	0	54	0.89	0.69	-0.94
Clay (%)	11	7	11.29	0	67	1	2.43	7.67

Variable	Mean	Median	SD	Min	Max	CV	Skewness	Kurtosis
BD (g/cm^3)	0.99	0.98	0.24	0.49	1.46	0.24	-0.003	-0.94
PR (MPa)	2.42	1.89	1.18	0.5	4.8	0.48	0.86	-0.49
2002								
pH	4.88	4.9	0.44	3.7	5.8	0.09	-0.19	-0.38
N (%)	0.23	0.21	0.14	0.02	0.59	0.59	0.47	-0.67
OM (%)	5.41	4.53	3.73	0.07	16.31	0.69	0.71	-0.17
P (mg/kg)	12.02	11	7.95	0	37	0.66	0.69	0.45
K (cmol(+)/kg)	0.18	0.15	0.12	0	0.53	0.66	0.56	-0.57
Ca (cmol(+)/kg)	2.81	2.56	1.86	0.35	9.1	0.66	1.28	1.66
Mg (cmol(+)/kg)	1.67	1.33	1.16	0.17	4.6	0.69	0.72	-0.55
Na (cmol(+)/kg)	0.2	0.15	0.12	0.05	0.65	0.58	1.38	1.76
Sand (%)	67	74	25.33	20	96	0.37	-0.39	-1.42
Silt (%)	18	10	16.34	1	58	0.89	0.68	-0.83
Clay (%)	14	10	12.59	1	51	0.88	1.11	0.37
BD (g/cm^3)	0.79	0.68	0.23	0.34	1.46	0.29	1.62	1.72
PR (MPa)	2.2	1.37	1.39	0.3	4.8	0.63	0.72	-1.03

OM, organic matter; BD, bulk density; PR, penetration resistance at 5 cm depth.

A correlation matrix between soil properties is shown in Figure 5.2. Rectangles were drawn around the correlation matrix plots based on the hierarchical clustering of correlation values. High positive correlation was observed for N and organic matter as well as between Mg and Ca, Ca and clay, Ca and silt, Mg and silt, and Mg and clay. Sand content had a strong negative correlation with Ca and Mg; pH had a strong negative correlation with Al.

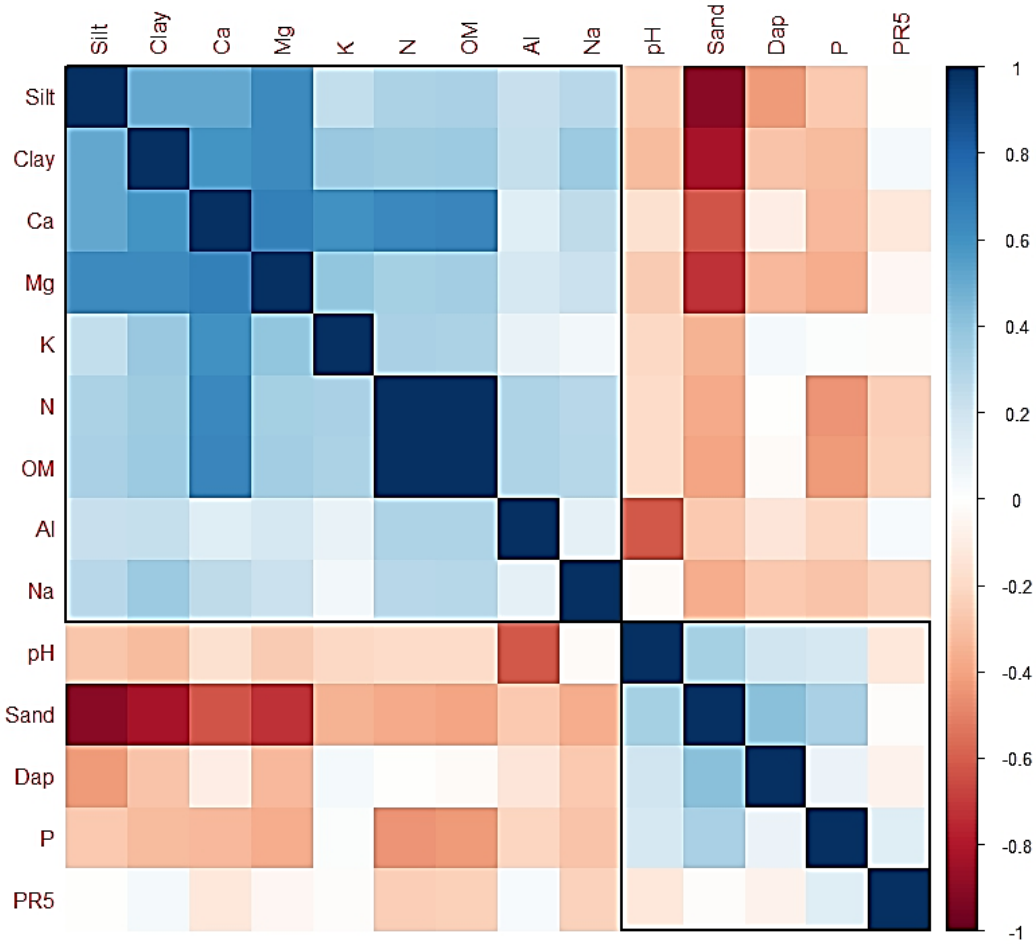

Figure 5.2. Correlation matrix between soil properties in the study area.

5.3.2 Geostatistical analysis of soil properties

Spatial continuous estimation of soil properties was carried out with ordinary kriging following the spatial correlation structures described with the variograms for spatial interpolation of the soil properties to be used for delineation of homogeneous zones. Experimental variograms were computed for this purpose (Appendix 2[‡]), and theoretical models were a good fit in most cases for the soil properties (Table 5.2).

[‡] Appendices for this chapter can be downloaded from: https://data.zef.de/?uuid=7315196f-60aa-4eb3-87ca-d49b0531f22e

Kriging maps were developed to show spatial distribution of soil properties in the four selected areas undergoing restoration (Appendix 3).

Table 5.2. Geostatistical analysis of soil physicochemical properties. Maximum likelihood estimation of parameters of theoretical variogram for nugget variance ($\boldsymbol{\tau^2}$), partial sill ($\boldsymbol{\sigma^2}$), practical range ($\boldsymbol{\varphi}$, m), nugget to sill ratio (NSR, %), anisotropy angle ($\boldsymbol{\psi_A}$) and anisotropy ratio ($\boldsymbol{\psi_R}$).

Parameter	**pH**	**N**	**OM**	**P**	**K**	**Ca**	**Mg**	**Sand**	**Silt**	**Clay**	**BD**	**PR**
						2014						
Model	Mat	Exp	Exp	-	Cub	Exp	Sph	Sph	Mat	Sph	Cub	Gau
τ^2	0.14	0	5.09	-	0.15	0	0.36	0.02	0.01	0	0.01	0.6
σ^2	0.09	0.015	12	-	0.25	4.83	0.58	0.06	0.03	0.01	0.04	0.46
$\boldsymbol{\varphi}$ **(m)**	200	173.1	262.1	-	383.3	163.1	202.8	567.1	100	146.5	402.8	77.9
NSR (%)	155	0	42	-	60	0	62	33	33	0	25	130
ψ_A	0	0	0	-	0	0.385	0	0	0	1.23	1.07	0.68
ψ_R	2.54	1	1	-	1.07	3.15	11.86	10.5	12.96	1.39	1.46	6.08
ME	0.004	9e-4	9e-4	-	4e-4	0.019	0.006	3e-5	5e-4	8e-4	0.001	0.01
MSE	0.005	0.01	1e-4	-	0.024	0.007	0.88	2e-4	0.002	0.009	0.002	0.005
RSME	0.42	0.09	2.79	-	0.07	1.88	1.03	0.18	0.11	0.09	0.17	0.89
						2010						
Model	Gau	PW	PW	Sph	Sph	Cub	Sph	Sph	Sph	PW	Sph	-
τ^2	0.23	0.007	1.38	14	0.09	2.53	0.71	0.01	0.07	0.01	0	-
σ^2	0.02	0.01	2.31	34.32	0.01	2.61	0.38	0.05	0.21	0.004	0.02	-
$\boldsymbol{\varphi}$ **(m)**	100	100	100	165.9	99.86	364.4	339.7	196.6	102.8	174.2	118.9	-
NSR (%)	1150	70	60	41	900	97	186	20	33	250	0	-
ψ_A	0	0	0	0.006	0	0	0	0.70	0.69	0.83	0.16	-
ψ_R	1	1.55	1	1	1	2.04	1.57	2	2.06	1	2.7	-
ME	0.001	0.001	0.03	0.16	2e-4	0.013	0.007	0.008	0.007	3e-5	5e-4	-
MSE	0.001	0.006	0.009	0.012	0.003	0.003	0.004	0.014	0.02	9e-5	0.002	-
RSME	0.52	0.56	1.57	6.18	0.11	1.77	0.89	0.21	0.13	0.12	0.14	-
						2006						
Model	-	Exp	Exp	Sph	Sph	Sph	Sph	Sph	Sph	Exp	Exp	Sph

τ^2	-	0.002	1.2	38	0	0.5	0.6	0.04	0.004	0	0.01	0.9
σ^2	-	0.016	9.79	126.6	0.011	1.03	0.05	0.7	0.023	0.009	0.058	0.34
φ (m)	-	352.4	307.6	575.4	128.9	202.1	200	353.1	200	35.68	269.4	200
NSR (%)	-	13	12	30	0	49	1200	6	17	0	16	264
ψ_A	-	0.007	0	0	0	0	1e-4	0	0.31	0	0	0
ψ_R	-	1	1	1	1	1	1.15	1	1.79	1	1	1
ME	-	5e-4	0.014	0.043	2e-4	0.016	8e-4	5e-4	0.003	5e-4	0.001	0.001
MSE	-	0.004	0.004	0.002	0.004	0.002	5e-4	9e-4	0.016	0.004	0.003	6e-4
RSME	-	0.074	1.91	8.06	0.096	1.14	0.78	0.20	0.15	0.096	0.168	1.13
2002												
Model	Sph	Sph	Sph	Sph	Sph	Sph	Sph	Sph	Sph	Sph	Sph	Mat
τ^2	0.12	0.012	10	20	0.01	1	0.6	0	0.005	0.001	0.03	0.8
σ^2	0.091	0.006	2.74	44.02	0.006	1.22	0.88	0.074	0.035	0.015	0.03	0.86
φ (m)	524.7	178.3	201.2	768.6	200	119.2	526.7	482.8	745.7	157.5	259.9	185.22
NSR (%)	131	200	364	45.43	166	82	68	0	14	7	100	93
ψ_A	0	0.831	0.82	0.84	0.86	0.32	0	0	0.91	0.16	0.53	0
ψ_R	10.69	6.85	6.25	2.21	4.61	1	1	1	3.72	1.25	2.71	1
ME	3e-4	1e-4	5e-4	0.014	6e-4	0.005	0.01	0.004	0.002	0.001	0.005	0.005
MSE	5e-4	2e-4	1e-4	0.001	0.006	0.002	0.005	0.018	0.012	0.008	0.061	0.002
RSME	0.41	0.12	3.45	6.19	0.11	1.70	0.94	0.18	0.12	0.096	0.19	0.85

Sph: Spherical, Mat: Matern, Exp: Exponential, PW: Power exponential, Cub: Cubic, Gau: Gaussian.
OM, organic matter; BD: Bulk density, PR: Penetration resistance at 5 cm depth. Missing values correspond to parameters for which spatial interpolation could not be conducted using ordinary kriging.

Four areas undergoing restoration since 2002, 2006, 2010 and 2014 were selected for geostatistical analyses. Density graphs for each parameter in each restoration area are provided as supplementary material (Appendix 1). Spatial autocorrelation was calculated through Moran and Geary C tests and Moran correlogram. Spatial autocorrelation was calculated for the majority of the soil parameters, with the exception of K, sand content and penetration resistance in the plot established in 2014, sand content in the plot established in 2010, and K, sand and silt content in the plot established in 2002. Moran scatter plots were elaborated and significant inliers were removed before proceeding with further geostatistical analysis.

Non-parametric semivariograms were calculated for each soil parameter in the four areas (Appendix 2), and theoretical models were used to find the best fit for each case (Table 5.2). For the restoration area established in 2014, OM (σ^2=12, φ=262.1 m), Ca (σ^2=4.83, φ=163.1 m) and Mg (σ^2=0.58, φ=202.8 m) exhibited the highest spatial variability, followed by penetration resistance at 5 cm depth (σ^2=0.46, φ=77.9 m) and K (σ^2=0.25, φ=383.3 m). For the restoration area established in 2010, the highest spatial variability was exhibited by P (σ^2=34.32, φ= 165.9 m), followed by Ca (σ^2=2.61, φ=364.4 m), OM (σ^2=2.31, φ=100 m) and Mg (σ^2=0.38, φ=339.7 m). For the restoration area established in 2006, the highest spatial variability was exhibited by P (σ^2=126.6, φ= 575.4 m), followed by OM (σ^2=9.79, φ=307.6 m), Ca (σ^2=1.03, φ=202.1 m) and sand content (σ^2=0.7, φ=353.1 m). For the restoration area established in 2002, the highest spatial variability was exhibited by P (σ^2=44.02, φ= 768.6 m), followed by OM (σ^2=2.74, φ=201.2 m), Ca (σ^2=1.22, φ=119.2 m) and Mg (σ^2=0.88, φ=526.7 m). Furthermore, the nugget to sill ratio (NSR) shows that for the restoration area established in 2014 most of the variables exhibit moderate to weak spatial dependency, with the exception of N, Ca and clay content. For the restoration area established in 2010, only bulk density exhibited strong spatial dependency. For the restoration area established in 2006, most of the variables exhibited strong spatial dependency, with exception of Ca, Mg and penetration resistance. For the restoration area established in 2002, most of the variables exhibited weak spatial dependency, with exception of the textural variables.

Most of the variograms show a considerable nugget effect explained by the fact that variability in soil properties can occur at a scale smaller than the minimum lag distance (Moral et al., 2010). Furthermore, the results of the geostatistical analysis show that OM, P, and exchangeable cations (Ca, Mg) exhibited the highest spatial variability in the four restoration areas.

The high spatial variability of P content in the deposits can be explained by the primary origin of the alluvial deposits considering that the sand fraction is predominant. This is because a fairly high proportion of the P in sand fractions of alluvial soils is of primary origin, whereas the P in clay fractions is mostly the result of the accumulation of both organic and inorganic P (Syers et al., 1969). Furthermore, P retention and release has been shown to be influenced more strongly by the parent material and thus sedimentation conditions in young floodplain soils than by pedogenetic processes (Lair et al., 2009). In addition to the variability inherent to the parent material, some management practices can also influence P spatial variability. For example, the irregular return of manure and urine is a heterogeneous supply of nutrients to the soil, which can also result in heterogeneous plant growth with a proliferation of roots and heterogeneous increase in the rate of P absorption (Corazza et al., 2003).

High variability and distribution of organic matter can be explained by the fact that these materials are a complex mixture of the materials deposited during alluvial-gold exploitation and natural recent OM. It is well known that the OM content in sediments usually exhibits substantial spatial variability, especially in areas where historical gold mining has taken place (Nascimento et al., 2012). Organic matter is easily affected by climatic conditions, and in mining deposits, it can easily be washed out and be affected by erosion (Komnitsas et al., 2010). In addition to the inherent random distribution of OM in these deposits, the main changes are a consequence of the input and incorporation of fresh OM from vegetation in the surface layer (Huot et al., 2014). Furthermore, even in poorly revegetated areas, OM can be produced in limited quantities, which can also explain its high spatial variability. The composition of tree species can also change the OM in mixed forests and reflects the chemical characteristics of the various tree species present in the stand (Kooch and Bayranvand, 2017). High spatial variability of OM can also explain the high variability of exchangeable cations observed in the study area, which can be due to high differentiation of the OM content in the deposits. Alluvial soils are usually characterized by low K and Mg, therefore most of the ions occur in the horizons enriched with OM as consequence of the biological accumulation of these components (Bartkowiak and Dlugosz, 2010).

To summarize the variability of the soil properties of the four restoration areas, a MULTISPATI PCA analysis (Dray et al., 2008) was performed. This multivariate spatial analysis has an advantage over classical PCA as the principal components derived from this analysis maximize the spatial autocorrelation between sites. This method accounts for the spatial position of the sampling sites through the construction of a neighboring relationship between sites. This allows the detection of map trends in the multivariate distribution of topsoil characteristics, showing strong spatial structures on the first few axes (Schneider et al., 2016). In this study, we calculated the neighboring relation by considering the relation of each point with its three nearest neighbors.

5.3.3 Spatial regression of vegetation indices and soil properties as explanatory variables

To analyze the interrelations among soil physicochemical properties and NDVI as an indicator of potential productivity of the areas, a spatial regression was conducted by means of an error model. Initially, a linear regression was conducted to analyze the relation between NDVI and soil physicochemical properties. Spatial autocorrelation for the residuals of this linear model was significant. Moran's *I* statistics of 0.93 ($p < 0.001$) for the restoration area established in 2014, of 0.96 ($p < 0.001$) for that established in 2010, of 0.94 ($p < 0.001$) for that established in 2006, and of 0.93 ($p < 0.001$) for that established in 2002 strongly suggest that standard regression estimates cannot be trusted. Therefore, it was necessary to include the spatial structure of the data in the regression analysis. For the restoration area established in 2014, pH, P, K, silt content, bulk density and penetration resistance at 5 cm depth are significant explanatory variables of NDVI (Table 5.3). There is an inverse relation between pH and bulk density with NDVI and a positive relationship of K with NDVI. In addition, there is a marginal positive relation between silt content and penetration resistance with NDVI. For the restoration area established in 2010, pH still has a significant negative relation with NDVI, K content a positive relation with NDVI, and bulk density a significant negative relation with NDVI. Marginal positive relations are observed among sand and silt content with NDVI, and marginal negative relations are observed among P and Mg content with NDVI. For the restoration area established in 2006, K and bulk density have a positive relation with NDVI. A positive marginal relation is observed between P and NDVI, which is negative between Ca and penetration resistance with NDVI. For the restoration area established in 2002, pH and N have a positive relation with NDVI.

For the four restoration areas, the major spatial variations of the NDVI are explained mainly by spatial variations of pH, bulk density and K content. Nitrogen content becomes a significant explanatory variable only for the restoration area established in 2002 (Table 5.3). These properties exhibit relatively low spatial variability and overall moderate to weak spatial dependence (Table 5.2). K has been found to be an influential variable on NDVI in previous studies (Whetton et al., 2017), however, its influence is higher in younger areas undergoing restoration. The pH value also has a higher influence in younger areas, and the same behavior is observed for bulk density. It should be noted that for restoration areas established in 2002, more soil properties are considered to have a significant influence on NDVI, such as P, Mg and textural variables when compared with younger areas. Therefore, the relative importance of pH, K and bulk density decreases.

Table 5.3. Spatial regression coefficients of soil properties as explanatory variables of NDVI. Significance is assumed for p-value < 0.001.

Property	**2014**		**2010**		**2006**		**2002**	
	β	p-value	β	p-value	β	p-value	β	p-value
pH	-0.17	3.2e-13	-0.07	1.81e-9	-	-	0.06	<2e-16
N (%)	-1.04	0.06	-0.19	0.005	1.21	0.013	0.11	<2e-16
OM (%)	0.01	0.25	0.001	0.012	-0.045	0.016	-0.004	0.011
P (mg/kg)	-0.002	0.002	-0.003	3.5e-5	0.004	2.9e-12	-0.006	1.8e-4
K (cmol(+)/kg)	0.95	4.5e-12	0.473	1.12e-6	0.743	<2.2e-16	-0.044	<2e-16
Ca (cmol(+)/kg)	-0.007	0.41	0.007	0.048	-0.034	1.2e-4	-0.006	0.003
Mg (cmol(+)/kg)	-0.022	0.25	-0.023	3.46e-5	0.049	0.002	-0.021	3.4e-4
Sand (%)	0.001	0.02	0.001	2.1e-4	-5e-4	0.526	3.2e-4	<2e-16
Silt (%)	0.007	1.1e-10	0.007	<2e-16	-0.01	<2e-16	-0.165	0.081
Clay (%)	0.002	0.13	0.001	0.012	0.003	0.009	0.003	<2e-16
BD (g/cm^3)	-0.68	<2e-16	0.13	1.67e-6	0.18	1.202e-7	-0.051	<2e-16

Property	**2014**		**2010**		**2006**		**2002**	
	β	p-value	*β*	p-value	*β*	p-value	*β*	p-value
PR (MPa)	0.035	6.1e-11	-	-	-0.011	0.107	-9.3e-4	0.42
Intercept	1.98	< 2e-16	0.85	< 2e-16	0.54	2e-7	0.69	<2e-16
p-value (model)	<2e-16		<2e-16		< 2e-16		<2e-16	
Residuals								
Min	-0.78		-1.84		-1.04		-1.77	
1Q	0.032		0.012		-0.018		-0.011	
Median	0.002		0.002		0.003		0.003	
3Q	0.031		0.014		0.022		0.016	
Max	0.795		0.918		0.686		0.598	

OM, organic matter; BD: Bulk density, PR: Penetration resistance at 5 cm depth. Missing values correspond to parameters for which spatial interpolation could not be conducted using ordinary kriging

5.3.4 Delineation of homogeneous zones based on soil properties

To summarize the variability of the soil properties, a MULTISPATI principal component analysis (MULTISPATI-PCA) of the scaled values was performed. In the restoration area established in 2014, the first and second eigenvalues exhibited higher values with loadings of 55% and 20%, respectively (Table 5.4), thus explaining the high total variability (76%). The graphical display of the MULTISPATI-PCA analysis (Figure 5.3) allows visualizing the spatial correlation structure between the variables to be used for cluster analysis. For the restoration area established in 2014, clay and Ca contents were positively correlated, as well as Mg, OM and N. The first principal component exhibited high loadings for N, OM, Mg, sand and silt content with average loading values of 0.35 for each soil parameter. The second principal component exhibited high loadings for K (0.59), bulk density (0.49), Ca (0.36) and P (0.35). The map of the first principal component (Figure 5.4) shows that the spatial pattern of the eigenvalues resembles the spatial pattern observed for N and OM (Appendix 3). Furthermore, the spatial pattern of the second principal component (Appendix 4) resembles that of the exchangeable cations K and Ca.

For the restoration area established in 2010, the first and second eigenvalues were associated to loadings of 51.16 and 16.66, respectively (Table 5.4), together explaining 67.83% of the total variability. The graphical display of the MULTISPATI-PCA analysis (Figure 5.3) for this plot shows that N, Ca, OM and K were positively correlated, as well as P content and pH. The first principal component exhibited relatively high loadings for all textural variables (0.35), and Ca (0.33) and Mg (0.31) content. The second principal component exhibited higher loadings for K (0.44), Ca (0.36) and bulk density (0.36). The map of the first principal component (Figure 5.4) shows that its spatial pattern resembles that of Mg and sand. The map of the second principal component (Appendix 4) shows that its spatial pattern resembles that of K content.

For the restoration area established in 2006, the first and second eigenvalues are associated to loadings of 36.192 and 31.983, respectively, together explaining 68.18% of the total variability (Table 5.4). The graphical display of the MULTISPATI-PCA analysis (Figure 5.3) shows a strong positive correlation between the pairs clay and Mg, K and Ca, and OM and N. The first principal component exhibited high loadings for Mg (0.41), sand (0.48), silt (0.42), clay (0.38) and bulk density (0.41). The second principal component exhibited higher loadings for N (0.49), OM (0.48), K (0.41), and Ca (0.47). Maps of the first principal component (Figure 5.4) show that its spatial pattern resembles that of sand and bulk density (Appendix 3). The map of the second principal component (Appendix 4) shows that its spatial pattern resembles that of Ca content.

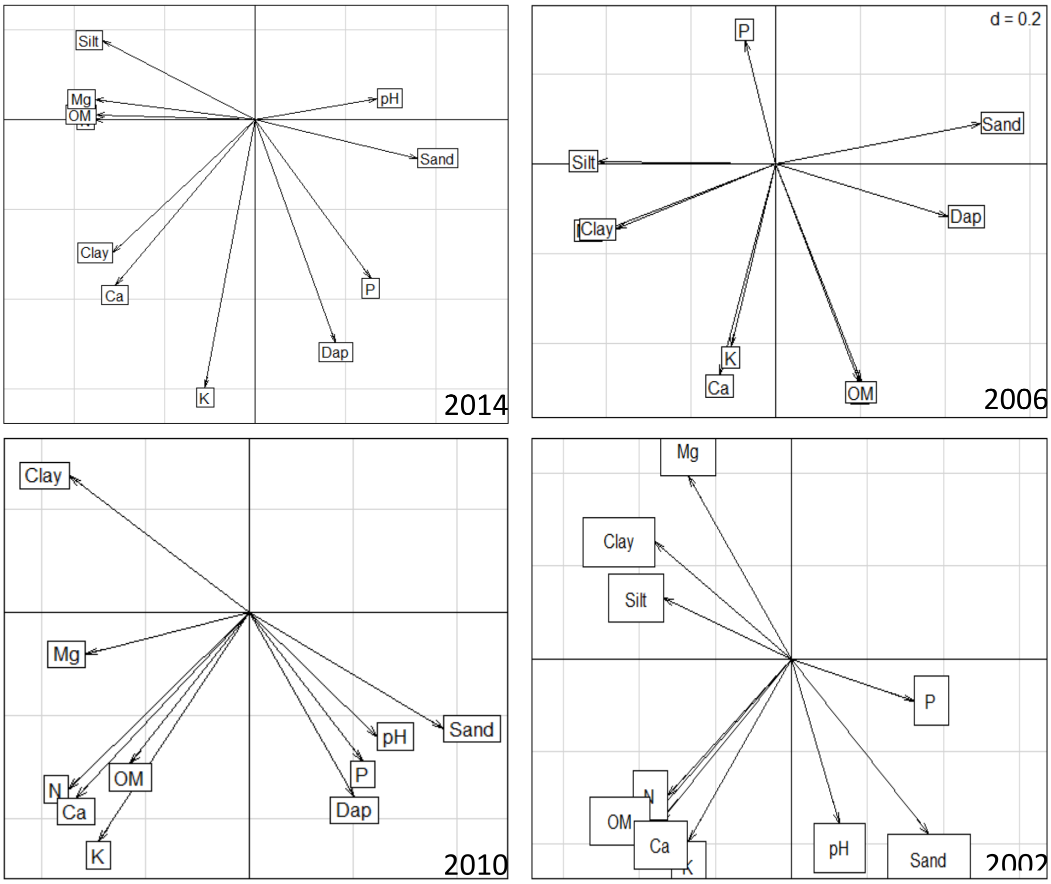

Figure 5.3. Graphical display of the first two axes of MULTISPATI-PCA analysis with soil properties pH, N, OM, P,K, Ca, Mg, Na, sand, silt, clay, bulk density, penetration resistance at 5 cm for areas undergoing restoration since 2014, 2010, 2006 and 2002.

Table 5.4. Principal component analysis for soil properties pH, N, OM, P, K, Ca, Mg, Na, sand, silt, clay, bulk density, penetration resistance at 5 cm.

Year of establishment	**Principal component**	**Eigenvalue**	**Component loading**	**Cumulative loading**
2014	PC1	6.1040	55.49	55.49
	PC2	2.2159	20.145	75.64
	PC3	1.0229	9.299	84.93
	PC4	0.5884	5.349	90.28
	PC5	0.3431	3.119	93.40

Year of establishment	**Principal component**	**Eigenvalue**	**Component loading**	**Cumulative loading**
2010	PC1	5.6277	51.162	51.16
	PC2	1.8333	16.666	67.83
	PC3	1.0570	9.610	77.44
	PC4	0.7417	6.743	84.18
	PC5	0.5233	4.758	88.94
2006	PC1	3.6192	36.192	36.19
	PC2	3.1983	31.983	68.18
	PC3	1.1023	11.023	79.20
	PC4	0.7553	7.553	86.75
	PC5	0.4855	4.855	91.61
2002	PC1	5.1786	51.786	51.79
	PC2	1.6878	16.878	68.66
	PC3	1.1639	11.639	80.30
	PC4	0.5765	5.765	86.07
	PC5	0.4311	4.311	90.38

For the restoration area established in 2002, the first and second eigenvalues are associated to loadings of 51.786 and 16.878, respectively, together explaining 68.66% of the total variability (Table 5.4). The graphical display of the MULTISPATI-PCA analysis (Figure 5.3) shows a strong positive correlation between N and OM. The first principal component exhibited relatively high loadings for all textural variables with an average of 0.36 and for N (0.32), OM (0.37) and P content (0.32). The second principal component exhibited relatively high loadings for pH (0.35), OM (0.35), K (0.39), Ca (0.35) and Mg (0.39). The map of the first principal component (Figure 5.4) shows that its spatial pattern resembles that of N and OM. The map of the second principal component (Appendix 4) shows that its spatial pattern resembles that of Ca. For all areas, the first and second principal components were correlated to all soil parameters. Therefore it is clear that all soil parameters represent significant sources of variability, and need to be analyzed for further classification as explained by the two first principal components to be used for clustering.

Due to the fact that a high percentage of the variability (≈70%) can be explained by the first two principal components in all restoration plots, only the first two axes were used for the cluster analysis. Euclidean distance was used as a similarity distance in the optimization function of the clustering algorithm. A fuzzy c-means algorithm was applied to the two first principal components to form 2, 3 and 4 clusters. The validity of the clusters was assessed through the fuzzy validity measures associated with the indices Xie-Beni, Fukuyama Sugeno, partition coefficient and partition entropy (Table 5.5). For all indices except partition coefficient, the optimum number of classes is indicated by the lowest index values. For the area undergoing restoration since 2014, the Xie-Beni and partition entropy indices indicate that two clusters should be selected for delineating homogeneous zones; however, Fukuyama Sugeno and partition coefficient suggest four clusters. In addition, the summarizing indices proposed by Galarza et al. (2013) suggest four clusters. For the area undergoing restoration since 2010, the Xie-Beni index, partition entropy and partition coefficient suggest two clusters; however, the Fukuyama Sugeno and the summarizing indices suggest four clusters. However, the use of these indices only provides a statistical metric but does not consider whether the output realistically corresponds to field areas that can be differently managed. Therefore, three clusters were selected to delineate homogeneous zones in the areas undergoing restoration since 2014 and 2010 (Figure 5.5).

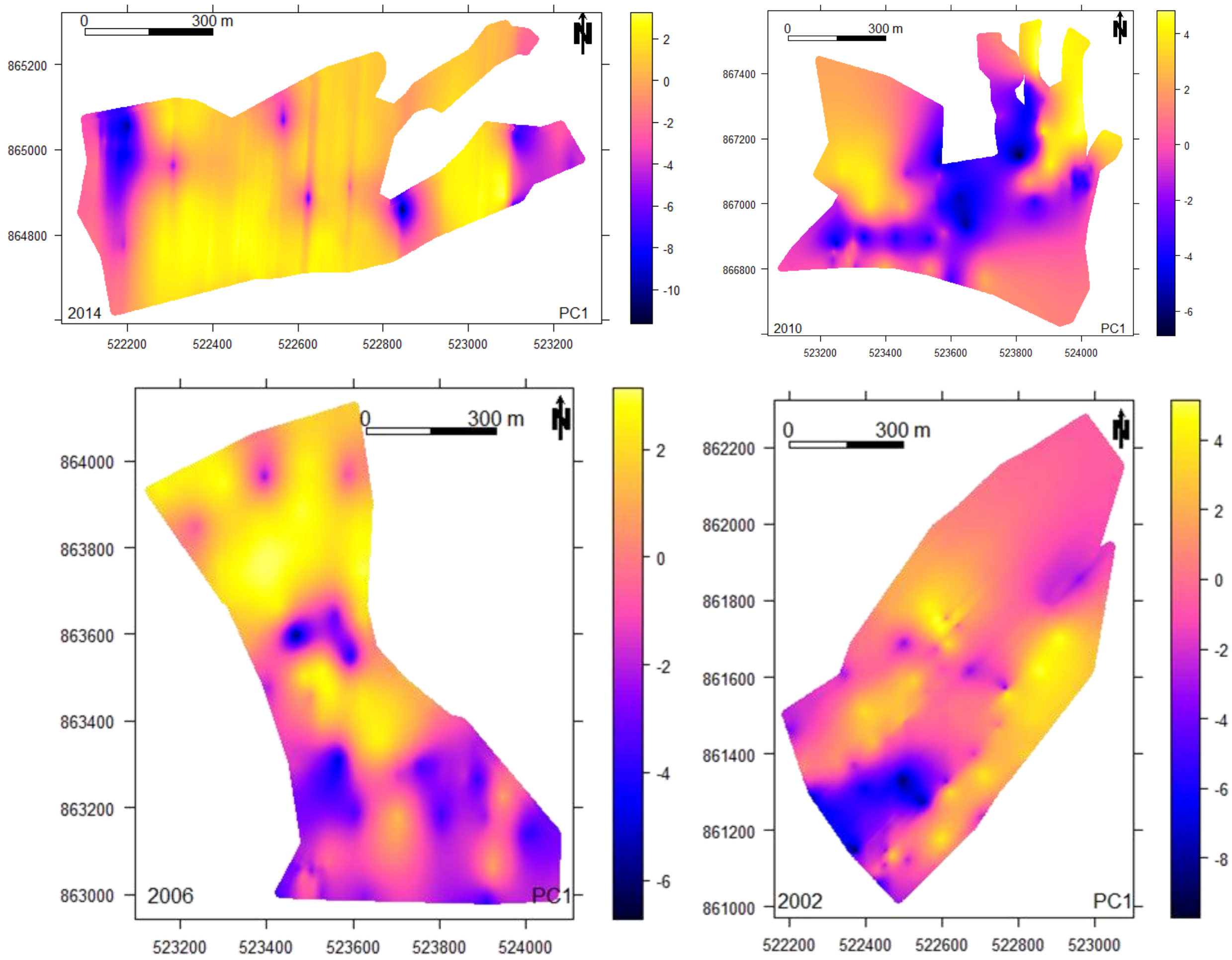

Figure 5.4. Maps of the first principal component for areas undergoing restoration since 2014, 2010, 2006 and 2002.

Table 5.5. Validity of clusters from fuzzy k-means cluster results. XB: Xie Beni, FS: Fukuyama Sugeno, PC: partition coefficient, PE: partition entropy, SI: summarizing index proposed by Galarza et al. (2013).

Year of establishment	**Index**	**2 clusters**	**3 clusters**	**4 clusters**
2014	XB	5.043e-07	1.077e-06	6.758e-07
	FS	-1.610e+06		
	PC	7.581e-01		

Year of establishment	**Index**	**2 clusters**	**3 clusters**	**4 clusters**
	PE	3.919e-01	-1.485e+06	-1.452e+06
	SI	1.220e+06	6.158e-01	5.322e-01
			6.725e-01	8.865e-01
			9.150e+05	7.732e+05
2010	XB	5.885e-07	1.064e-06	7.228e-07
	FS	-1.230e+06	-1.297e+06	-1.336e+06
	PC	6.864e-01	5.318e-01	4.839e-01
	PE	4.848e-01	8.069e-01	9.715e-01
	SI	1.792e+06	1.608e+06	1.375e+06
2006	XB	6.194097e-07	3.202407e-07	3.976904e-07
	FS	-5.291395e+05	-7.322126e+05	-7.346625e+05
	PC	1.000000e+00	1.000000e+00	1.000000e+00
	PE	3.317797e-01	4.245127e-01	4.763111e-01
	SI	529139.5	732212.6	734662.5
2002	XB	8.261e-07	7.682e-07	5.340e-07
	FS	-8.072e+05	-1.335e+06	-1.637e+06
	PC	6.314e-01	5.332e-01	4.918e-01
	PE	5.485e-01	8.006e-01	9.574e-01
	SI	5.097e+05	7.121e+05	8.052 e+05

For the area undergoing restoration since 2006, the Xie-Beni index suggests three clusters for the delineation of homogeneous zones; however the Fukuyama Sugeno, the partition entropy and summarizing index suggest two clusters. Therefore, two homogeneous zones were delineated based on these criteria and also based on the fact that the delineated areas can be differentially managed by the farmers (Figure 5.5). For the area undergoing restoration since 2002, the Xie-Beni index suggests that four clusters, the Fukuyama Sugeno suggests the selection of three clusters, the partition coefficient two clusters, as well as the partition entropy and the summarizing index. Four clusters were selected for the delineation of homogeneous zones in this area.

Indices were used to assess the appropriateness of the clustering algorithm. However, the division of the experimental field into a specific number of homogeneous zones depends not only on the statistical results of these tests, but also on a logical assessment of the delineated areas (Córdoba et al., 2016) with respect to the feasibility of developing different management strategies for each zone by the farmers, which can be analyzed by observing a better separation and less overlap among the delineated homogeneous zones. The number of zones depends on the inherent variability of the field, the type of variables selected for the delineation, weather and vegetation type established in the area, and sensitivity of measurements of within-field variability (Hagos, 2014). The homogeneous zones produced for this study can probably change when data from different seasons are used due to climatic factors that might influence soil properties.

5.3.5 Validation of delineated homogeneous zones with vegetation indices

NDVI maps were obtained using the reflectance data of the four multispectral image bands (red, green, near infrared, red edge) captured with a drone. The maps for the four areas undergoing restoration (Figure 5.6) will be used as a reference to validate the delineated homogeneous zones. The comparison of means for the soil parameters indicated statistically significant differences among the delineated homogeneous zones in the areas undergoing restoration since 2014, 2010, 2006 and 2002 (Table 5.6).

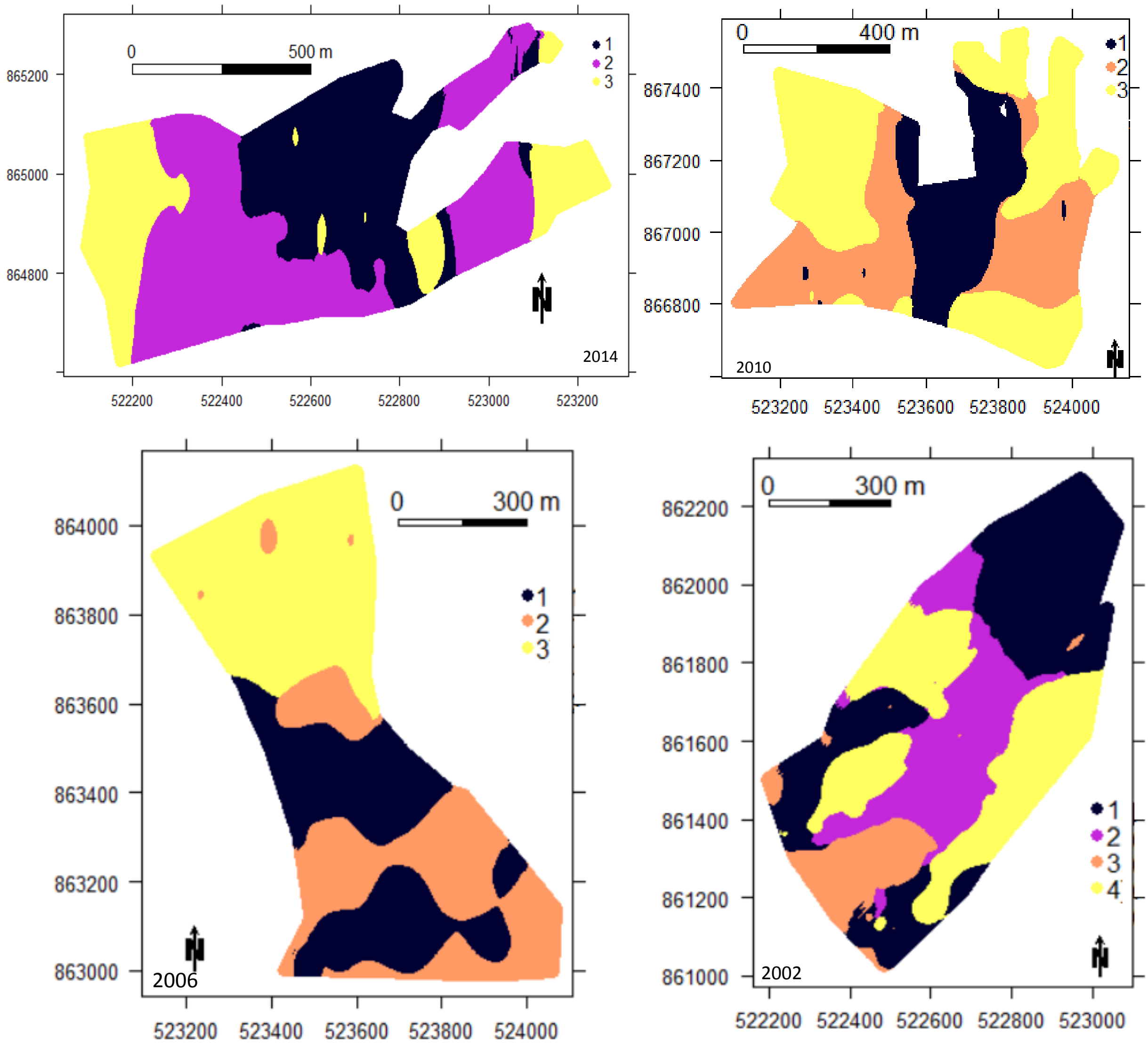

Figure 5.5. Homogeneous zones for optimum clusters in areas undergoing restoration since 2014, 2010, 2006 and 2002.

Table 5.6. Comparison of delineated homogeneous zones. Mean values of soil properties are shown for each zone. Significance codes (0 '***', 0.001 '**') illustrate significant differences.

Year	Zone	pH	N	OM	P	K	Ca	Mg	Sand	Silt	Clay	BD	PR5
2014	1	5.45	0.32	7.56	15.11	0.18	2.94	0.51	84.9	6.69	11.43	1.21	1.89
	2	5.48	0.31	7.29	12.69	0.04	1.25	0.36	88.9	5.45	5.48	0.95	1.65
	3	5.05	0.43	11.23	5.81	0.11	3.78	1.40	50.02	31.84	16.80	0.85	1.78
	p	**	***	***	***	***	***	***	***	***	***	***	***
2010	1	4.96	0.42	14.04	15.74	0.32	6.02	2.25	51.41	18.67	18.67	0.88	-
	2	5.04	0.21	4.64	12.95	0.21	3.47	1.89	51.32	20.29	20.30	0.81	-
	3	5.35	0.12	2.63	18.77	0.17	2.27	1.03	76.20	8.56	16.21	0.95	-
	p	**	***	***	***	***	***	***	***	***	***	***	-
2006	1	-	0.10	1.87	22.41	0.11	1.67	0.92	77.04	14.51	7.79	0.97	2.50
	2	-	0.19	4.26	15.69	0.22	3.11	1.59	58.41	24.57	16.31	0.84	2.39
	3	-	0.32	7.38	14.82	0.22	3.04	0.67	83.64	8.87	6.30	1.18	1.71
	p	-	***	***	***	**	***	***	***	***	***	***	***
2002	1	4.85	0.21	4.80	9.66	0.13	2.68	2.55	60.65	12.42	14.49	0.79	2.17
	2	5.13	0.23	7.22	11.82	0.23	3.76	1.09	81.17	8.80	8.13	1.05	1.46
	3	4.75	0.27	11.22	7.02	0.30	5.28	2.54	45.14	31.98	24.42	0.77	1.76
	4	5.02	0.18	2.70	17.58	0.11	1.66	0.85	86.31	4.56	6.35	0.69	2.29
	p	***	***	***	***	***	***	***	***	***	***	***	***

Note: Missing values due to the fact that the semivariogram for the parameter could not be fitted to any theoretical model, therefore, geostatistical interpolation of that soil property could not be performed.

For the area undergoing restoration since 2014, the three delineated zones exhibit a strongly acidic pH. Zone 1 exhibits on average higher sand content and bulk density, which implies that poor soil structure and that penetration resistance also might impair plant growth. The soil has high N and OM, moderate P content and moderate levels of exchangeable cations. This zone is also associated with the lowest mean NDVI values (Table 5.7), therefore it can be associated with the lowest productivity and poor health of the reestablished vegetation layer. Zone 2 also exhibits high N and OM, moderate P, and very low exchangeable cations. The sand content is also very high, however, the low bulk density and penetration resistance suggest very poor soil structure and limited capacity to support plant growth. Low mean NDVI (0.49) for this zone also suggests that the productivity of this area might not be very high and also limited crop growth. Zone 3 exhibits the lowest sand content and highest percentage of silt and clay. In addition, the bulk density values suggest satisfactory conditions for plant growth with no signs of soil compaction. The soil of this area has the highest N and OM, but low P, K, Ca and moderate Mg values. This zone is associated with the highest NDVI values, therefore can be considered as the most productive zone of this restoration area. When comparing the NDVI maps (Figure 5.6) and the delineated homogeneous zones (Figure 5.5) for the area undergoing restoration since 2014, clear coincidental patterns can be seen when observing areas with higher NDVI values, which correspond to those in zone 3, i.e. the most productive zone for this restoration area. This pattern can be observed more clearly for the area established in 2014 given that the vegetation cover corresponds only to spontaneous vegetation developed after a few months of the creation of this deposit, therefore the spatial variation of vegetation development is clearer in this area. The fact that the NDVI maps and the delineated homogeneous zones coincide is a useful verification of the validity of the delineated homogeneous zones by a continuous remotely sensed variable such as NDVI.

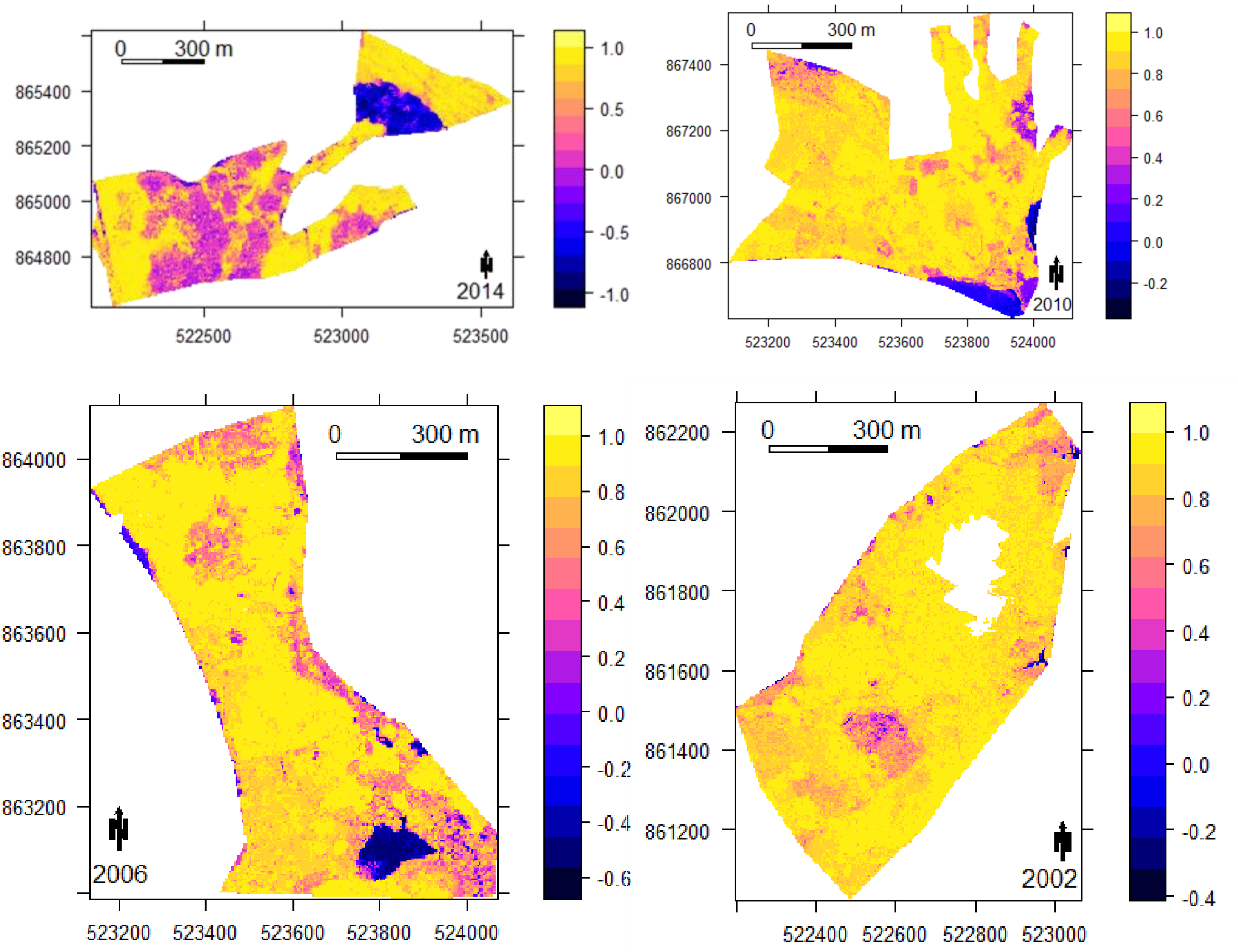

Figure 5.6. NDVI maps of areas undergoing restoration since 2014, 2010, 2006, and 2002 calculated from reflectance data of four bands captured with a drone coupled to a SenseFly multispectral sensor.

Table 5.7. Descriptive statistics of NDVI values for each management zone in the restoration plots established in 2014, 2010, 2006 and 2002. Significance codes: 0 '***', 0.001 '**', 0.01 '*', 0.05 '.' for one-way ANOVA and Tukey's multiple comparisons of means.

Year	Zone	Min	Median	Mean	Maximum	Global p-value	Pairwise Tukey HSD
2014	1	-0.79	0.44	0.46	0.99	<2e-16	2-1: 0.04***
	2	-0.75	0.51	0.49	0.99		3-1: 0.31***
	3	-0.71	0.73	0.77	0.99		3-2: 0.27***
2010	1	0.12	0.92	0.89	0.98	<2e-16	2-1: -0.03***
	2	-0.96	0.90	0.86	1		3-1: -0.13***
	3	-0.78	0.87	0.76	1		3-2: -0.10***
2006	1	-0.59	0.87	0.74	0.99	<2e-16	2-1: -0.02***
	2	-0.66	0.84	0.72	1		3-1: 0.07***
	3	-0.61	0.91	0.82	1		3-2: 0.10***
2002	1	-0.42	0.89	0.85	1	<2e-16	2-1: -0.0***
	2	-0.16	0.90	0.84	1		3-1: -0.008***
	3	0.04	0.88	0.87	1		4-1: 0.02***
	4	-0.85	0.90	0.88	1		3-2: 0.003**
							4-2: 0.03***
							4-3: 0.03***

The restoration area established in 2010 was also subdivided into three homogeneous zones. These zones exhibited the highly acidic pH values characteristic of these deposits. Zone 1 is characterized by loamy soils with bulk density values that suggest an adequate soil compaction for plant growth, high levels of OM, N and P, low values of K, and moderate Ca and Mg values. Zone 1 is associated with high NDVI values suggesting a high productivity potential and good health status of the vegetation. Zone 2 exhibits relatively similar textural properties to those of Zone 1, however, OM, N, P and exchangeable cations are much lower. The low bulk density indicates satisfactory soil consolidation, considering its textural properties. NDVI associated with Zone 2 is significantly lower compared to those of Zone 1. Therefore, even if the textural properties of the soil are similar, the nutrient content is a limiting factor for the potential productivity and successful vegetation reestablishment of Zone 2.

The restoration area established in 2006 was also subdivided into three homogeneous zones. Zone 3 exhibits the highest mean NDVI associated with the highest N and OM levels. On average, the bulk density in the loamy fine sand indicates high compaction that could inhibit root penetration. The P content is the lowest among the three zones. This zone also exhibits low exchangeable cations. However, the vegetation growth is not uniform (Figure 5.6), and some areas of this zone exhibit poor vegetation growth, therefore the mean NDVI might not be a good representation of the overall productivity of the zone. Zone 2 has a sandy loam soil with a bulk density that indicates a satisfactory degree of consolidation. However, penetration resistance indicates that this soil has high levels of compaction where very few plant roots can penetrate the soil. Mean NDVI is lowest in this zone, N is moderate, OM and P are high, and exchangeable cations low. Zone 1 also has sandy loam with higher bulk density and penetration resistance, which might inhibit plant growth due to severe compaction. This zone has a very low content of N and OM, P is high and exchangeable cations are very low. It has also relatively low mean NDVI compared with Zone 1. Therefore, it can be concluded that, in spite of the poor vegetation growth in some areas of Zone 3, high potential productivity can be expected in this here.

Four homogeneous zones were delineated in the area undergoing restoration since 2002. All zones exhibited highly acid conditions. Zone 2 had the lowest mean NDVI. This zone has a loamy/fine sand soil with moderate N and P, high OM, and low exchangeable cations. Average bulk density and penetration resistance suggest a level of soil consolidation that does not prevent root penetration. However, the low nutrient and high sand contents can explain the relatively low plant colonization of this zone. In contrast, Zone 3 and Zone 4 exhibited higher mean NDVI. Zone 3 has a sandy clay loam with the highest N and OM in this restoration area, low P and K, moderate Ca, and high Mg. Zone 4 also has a loamy/fine sand soil with a moderate degree of consolidation indicated by a relatively low bulk density; however, penetration resistance measurements indicate that some areas within the zone might be severely compacted and inhibit plant growth. Nitrogen and OM are moderate, P is high, and exchangeable cations are low.

Descriptive statistics of soil properties and NDVI of each zone indicate that the management scheme delineation using soil physicochemical variables allowed the creation of homogeneous zones with significantly different values. Literature has shown that the use of soil physicochemical properties sampled in different locations of a field is suitable to delineate potential homogeneous zones when analyzed together with a remotely sensed continuous variable (Farid et al. 2016). Variability of landscape measures analyzed through aerial images has been used in association with soil chemical properties to assess spatial patterns of crop yield through the delineation of homogeneous zones. However, the use of multiple years to describe and identify spatial patterns could provide broader opportunities for the farmers related to site-specific management of crop inputs and fertility management (Aaron et al., 2004). NDVI have been used in previous studies to delineate homogeneous zones aiming to control N inputs (Cicore et al., 2016) to identify variability in plant stress for management (Henik, 2012) and even as input to decision-support systems regarding plantation status (Katsigiannis et al., 2016).

5.4 Conclusions

Using a geostatistical approach, this study aimed to understand the spatial patterns of soil nutrients and physical properties in areas covered by gold mining waste undergoing revegetation with agroforestry systems. The NDVI was used as a proxy of productivity in the area and was correlated with soil properties by means of a spatial error model. Furthermore, management zones were delineated in the area and the NDVI was used for validation of the delineated areas.

The results of this analysis show that the studied areas have a predominantly low pH, and in spite of the high contents of N and OM, there is a lack of other necessary soil nutrients for almost the entire area. This is mostly explained by the nature of the alluvial deposits that cover the area, and by the technology used for washing the soil for gold extraction, which washes away nutrients important for plant growth. This lack of nutrients could be compensated through amendments prior to revegetation, including organic waste, compost or cover crops to buffer soil pH, improve water holding and cation exchange capacity of the substrate, establish active microbial communities, and provide nutrients to stimulate the reestablishment of vegetation. The relation of the NDVI as a proxy of productivity with soil properties strongly suggests that special attention should be paid to soil pH and exchangeable cations.

The high spatial variability of OM, exchangeable cations and P suggests that the application of amendments should consider this spatial heterogeneity, as the nutrient requirements may significantly differ even within areas of a few hundred meters. For this purpose, the delineation of homogeneous zones can be a helpful approach to support the farmers in decision making regarding soil fertility management.

Identification of management zones is the first step to implement site-specific soil management strategies. Understanding spatial variability of areas undergoing restoration will allow an overall increased productivity by developing strategies suitable to the characteristics of each field and its potential uses. In addition, areas suitable for crop establishment can be more accurately identified. Further studies need to be conducted to compare the seasonal variability of soil properties and its influence on the delineated management zones to understand the spatial dynamics of the restoration process. In addition, crop yield should be measured in each zone to understand the agronomic significance of the delineation process.

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6. USE OF UNMANNED AERIAL VEHICLE FOR THE ESTIMATION OF ABOVEGROUND BIOMASS AND SPECIES DIVERSITY IN RECLAIMED GOLD MINING WASTE DEPOSITS

Abstract

Alluvial gold mining projects leave a vast amount of waste that completely covers the natural soil and requires reclamation to return the disturbed area to a reference or pre-disturbance condition. Assessments of vegetation recovery in disturbed landscapes usually focus on parameters such as the abundance of trees, community composition of vegetation and biomass. Remote sensing is an important tool to estimate the biophysical parameters of vegetation by creating relationships between remotely sensed spectral variables and vegetation parameters. Therefore, the main objective of this study is to combine the use of multispectral images captured with an unmanned aerial vehicle (UAV) with a random forest model for prediction of tree species diversity and aboveground biomass in areas covered by gold mining waste undergoing reclamation with agroforestry systems. For this purpose, several vegetation indices, as well as image texture analysis, were used as predictors of aboveground biomass and species diversity. These measures can be used to evaluate how the reclaimed sites are responding to the interventions, and to determine the effect of management practices on forests and productivity of newly created ecosystems.

The random forest model achieved limited performance for the estimation of herbaceous biomass; however, its predictive capacity improved for the estimation of tree biomass and species richness. The model performance was the best when all predictors were included. The most important predictors of tree biomass were textural attributes whereas broadband greenness indices were the most important predictors of tree species richness. Areas with higher species richness did not coincide with areas of higher aboveground biomass (Figure 6.6 and 6.7), and tree biomass did not follow a clear

pattern of distribution within the analyzed plots. Furthermore, areas with higher species richness did not necessarily correspond to areas with higher aboveground tree biomass.

In younger restoration areas, vegetation growth was mainly in the form of pioneer shrubs with a few scattered areas with the pre-disturbance vegetation cover. Older reclamation areas did not have significantly higher species richness than younger. Special attention should be paid to fallow periods and management intensity of the areas undergoing restoration, and tree species selection for the agroforestry systems should minimize the use of exotic species and promote the use of native species that improve the diversity of the newly created ecosystems.

6.1 Introduction

Mining projects and other forms of industrial development often cause physical disturbances that require reclamation, i.e. the process of returning the disturbed area to a reference or pre-disturbance condition (Hird et al., 2017). Alluvial gold mining, particularly dredging operations, leaves a vast amount of waste that completely covers the natural soil, destroys riparian ecosystems and impacts river beds and valleys (Shlyakhov and Osipov, 2004). Waste deposits created by alluvial gold mining usually have low levels of macronutrients and an acidic pH that tend to disrupt soil formation processes and plant growth (Cooke and Johnson, 2002). Assessment of vegetation recovery in disturbed landscapes usually focuses on parameters such as the abundance of trees, community composition of vegetation, and plant height and branching architecture (Zahawi et al., 2015). These parameters can be used to evaluate how a particular site is responding to a restoration intervention and to determine the effect of management practices on forest development (Holl, 2002). Structural vegetation data, such as canopy height and coverage in conjunction with diameter at breast height and wood-specific gravity can be used to estimate aboveground biomass accumulation or stock (Chave et al., 2014).

Aboveground biomass is a basic ecological indicator for the study of environmental processes, as it provides important signs regarding the growth, light-use efficiency and carbon stocks in agroecosystems. Direct biomass estimation is through the destructive harvest of plants for estimation of dry biomass. However, over large areas, this is challenging, expensive and time-consuming. Therefore, remote sensing is an important tool to estimate biophysical parameters of vegetation by creating relationships between remotely sensed spectral variables and vegetation parameters (Li et al., 2016). To monitor structural data of vegetation, vegetation indices are the most widely used variables, however, their sensitivity is limited in areas with sparse vegetation (Wang et al., 2017a). Vegetation indices calculated from red and near-infrared (NIR) wavelengths, such as simple ratio (SR, (Chen, 1996)) and normalized difference vegetation index (NDVI, (Carlson and Ripley, 1997)) are good predictors of vegetation photosynthetic activity and are correlated to aboveground biomass. As aboveground green biomass increases, higher reflectance is caused by leaf internal multiple scattering in the NIR wavelengths, with less absorption in the red wavelengths due to chlorophyll absorption. However, SR and NDVI may lose sensitivity for monitoring aboveground biomass in sparse canopy situations due to the influence of soil background (Ren and Feng, 2015). To overcome this barrier, the red-edge band is more effective in differentiating the reflectance of the soil background, as this wavelength position covers chlorophyll absorption, leaf cell structure reflection and adds information for vegetation characterization (Schumacher et al., 2016). Therefore, red-edge indices are better for the estimation of aboveground biomass in semi-arid landscapes than traditional vegetation indices (Clevers et al., 2002).

In addition to the use of red-edge indices, it has been suggested to include texture attributes of aerial images, as the textural analysis discriminates the spatial variability of neighboring pixels independent from image tone. Texture analysis is an image processing technique that measures the variability in pixel values among neighboring pixels for a defined analysis window (Kelsey and Neff, 2014). Image texture has been observed in previous studies as a more accurate predictor of biomass than spectral vegetation indices (Eckert, 2012), as image texture discriminates the spatial variability of neighboring pixels independent from image tone (Kelsey and Neff, 2014). Another important contribution of adding texture measurements is the bias reduction of the predictions, as it tests the contribution of the surrounding pixels of the image to the biomass estimation (Xu et al., 2016). Of the many texture measures, the gray-level co-occurrence matrix (GLCM) is the most common texture measurement used to estimate aboveground biomass (Lu and Batistella, 2005), structural parameters of forests (Ozdemir and Karnieli, 2011) and species diversity (Wood et al., 2013).

Aerial images captured by unmanned aerial vehicles (UAV) provide a low-cost approach to meet the critical requirements of spatial, spectral and temporal resolutions for application in agricultural fields (Yang et al., 2017). The main benefits of using UAVs are simple mission planning, instantaneous operation with low manpower, imaging below cloud cover, and very high-resolution images (10 cm/pixel) of a vegetation canopy due to low flight altitudes (Schirrmann et al., 2016). The applications for these sensors include visible images for canopy surface modeling, crop height, biomass estimation, identification of physiological status, thermal imaging to detect water stress, and canopy structure parameters through the combination of different spectral bands (Yang et al., 2017).

The potential of UAV-acquired data to provide a cost-effective source of vegetation information is clear, however, a greater understanding of its strengths and weaknesses is needed if these data are to be considered as an alternative to traditional ground observations (Hird et al., 2017). For this purpose, a growing body of work has applied machine learning algorithms to classify vegetation and model structural traits or in combination with spectral datasets (Schumacher et al., 2016). Machine learning approaches provide efficient analysis of datasets with many potential predictor variables and often yield stronger models than those derived using simple linear regression methods (Anderson et al., 2018). Therefore, the combined analysis of remotely sensed data with field measurements of vegetation using a machine learning algorithm such as random forest (RF) can be a suitable option to effectively predict the spatial distribution of aboveground biomass (Wang et al., 2017b). Random Forest is a non-parametric regression tree method designed to generate robust predictions without over-fitting data (Tian et al., 2017).

The main objective of this study is to use vegetation indices, red-edge vegetation indices and image texture analysis as predictors of aboveground biomass and species diversity in areas covered by alluvial gold mining waste undergoing reclamation with agroforestry systems. The study focuses on a series of sites covered by alluvial gold mining waste undergoing reclamation for 0, 4, 8 and 12 years in north-west Colombia using multispectral images captured with a UAV and the RF model for prediction. It aims to contribute to the development of assessment protocols and environmental monitoring programs in reclamation areas with sparse vegetation to understand the spatial patterns of biomass production and species diversity distribution in the areas undergoing restoration.

6.2 Methodology

6.2.1 Study area

The study was conducted in north-west Colombia in the gold mining area of El Bagre, Antioquia (Figure 6.1). The area lies in a humid tropical forest zone (Espinal, 1992) with an average temperature of 28°C and an annual precipitation of 2.000 - 4.000 mm. The region has a dry season from November to March and a rainy season from April to October. The topography of the area is mostly flat. The area has the characteristics of low-lying forest that remains flooded most of the year, making productive agriculture, animal husbandry or forestry difficult. These areas are the most affected by the gold productive process of the company Mineros S.A.

Figure 6.1. Map of research area with sampled forest and herbaceous plots.

Areas to be restored are flattened with bulldozers to reduce the slope below 30% for the subsequent establishment of vegetation cover and agricultural land use. Gravel and sand deposits are the main areas of the restoration efforts. From the total area that needs to be restored, depending on location and stability of the deposits, specific areas are selected to implement agroforestry systems. The parcels are allocated to farmers that meet the requirements of the company, and partnership agreements are made. Resources for crop establishment as well as a subsidy are provided by the company to support the farmers initiating the restoration process.

The methodological approach of this study includes the steps shown in Figure 6.6.2. Vegetation measurements and wood density were determined to estimate woody biomass of trees using allometric equations developed by Chave et al. (2014). Aerial images captured with an unmanned aerial vehicle (UAV) were processed to create orthophoto mosaics that were subsequently used for the estimation of vegetation indices and extraction of texture attributes. Finally, ground- and image-based data sources were linked using a random forest (RF) algorithm to spatially predict forest and herbaceous biomass.

6.2.2 Vegetation survey

The forest cover was surveyed for aboveground biomass estimation and species identification in February 2017. The vegetation survey was performed in 21 circular plots of 10-m radius (250 m^2) distributed as follows: 2 plots located in the area undergoing revegetation since 2014, 2 plots on the area undergoing revegetation since 2010, 6 plots on the area undergoing revegetation since 2006, and 11 plots on the area undergoing revegetation since 2002. Trees with diameter at breast height in the range of 2.5 – 10 cm were measured within the plots. In total, 717 trees were selected for measurement of diameter at breast height, wood density, total height and species identification. The coordinates of the center of each plot were recorded using a portable GPS (Garmin eTrex 10, Germany). The angle and distance of each tree from the center of the plot were measured, and its coordinates estimated. Stem diameters of all trees within the plot were measured using a caliper. Tree height was measured using a Vertex IV (Haglöf, Sweden). Crown diameter was measured in north-south and east-west directions.

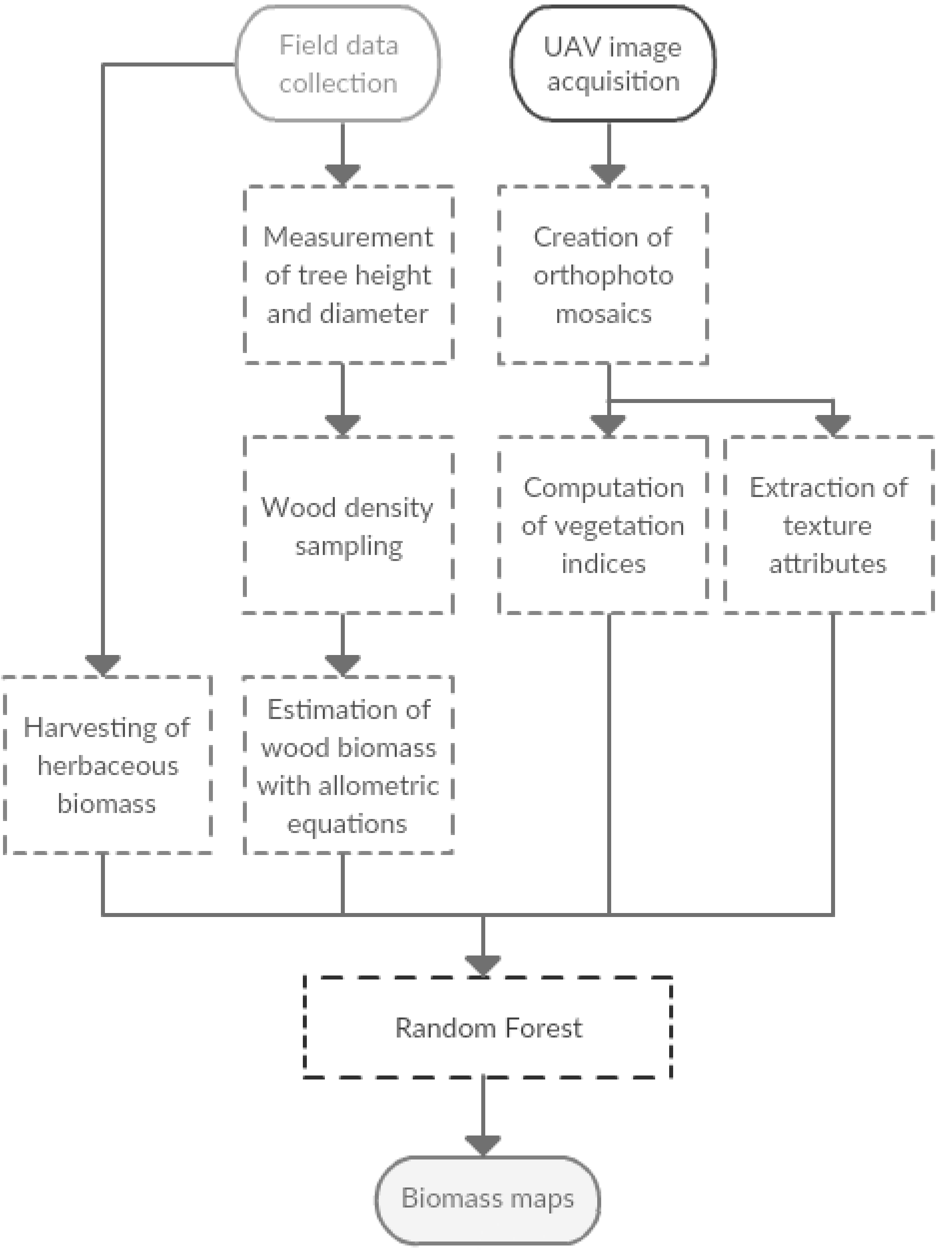

Figure 6.2. Flowchart of biomass estimation model.

For species identification, a preliminary analysis of the flora of the area was performed following the guidelines developed by Idárraga-Piedrahita et al. (2011), Cardona et al. (2010) and Cardona et al. (2011). For identification of the trees, leaf samples were collected from all individuals. The samples were preserved in alcohol for transportation to the laboratory, and subsequently dried and visually matched with species of the herbarium of the National University of Colombia. Some species could only be classified by genus because their reproductive morphology could not be determined, which is specifically relevant for the identification of *Vismia* sp. (Hypericaceae), *Casearia* sp. (Salicaceae), *Cordia* sp. (Boraginaceae) *and Licania* sp. (Chrysobalanaceae). Due to the complexity of their morphological and reproductive characteristics, genera *Inga* sp. (Fabaceae), *Citrus* sp. (Rutaceae), *Ficus* sp. (Moraceae) and *Piper* sp. (Piperaceae) were not classified at the species level.

6.2.3 Herbaceous biomass estimation

Herbaceous aboveground biomass growing spontaneously within the area and that was located outside of areas with forest cover was harvested at ground level in 120 plots (4 m^2 each) with 30 plots per area undergoing restoration since 2014, 2010, 2006 and 2002. The total fresh weight of the biomass was determined in the field, and a subsample of 500 g was oven-dried for 24 – 48 hours for determination of dry weight.

6.2.4 Tree biomass estimation

Tree biomass was derived from non-destructive measurements. Overall plots, 716 trees were selected for allometric measurements and species classification. Samples for estimation of wood density were taken using a three-threaded increment borer (Haglöf, Sweden) with 20 cm length and 0.5 cm diameter. The volume of the wood samples was estimated using the water displacement method, and dry weight was determined as indicated by Chave et al. (2014). Data collected in the field were used to determine biomass per individual according to the allometric equations established for tropical zones for trees with diameter at breast height >10 cm. Tree aboveground biomass (AGB_{est}) was estimated using the pantropical model developed by Chave et al. (2014):

$$AGB_{est} = 0.0673 \times (\rho D^2 H)^{0.976} \tag{1}$$

where tree diameter (D) is in cm, height (H) is in m, and wood density (ρ) is in g cm^{-3}. This model was selected as it performed well across forest types and bioclimatic conditions.

Allometric equations developed by Yepes et al. (2011) were used to estimate aboveground biomass of trees with diameter at breast height in the range of 2.5-10 cm.

$$AGB_{est} = \exp(2.4128 \ln D - 1.9968) \tag{2}$$

For areal estimation of tree biomass, the total biomass of each tree within the 21 circular plots was summed and divided by the area of the plot (250 m^2). The number of plots for ground measurements of tree biomass varied, since the forest cover in younger areas is smaller than in older areas, therefore, more than 50 % of the plots were located in restoration areas established in 2002 and 2006.

6.2.5 Aerial imagery

The commercially available Sensefly eBee UAV was used for taking aerial photographs (Sensefly, Chaseaux-Lausanne, Switzerland). A Parrot Sequoia multispectral sensor was adapted to the eBee for image collection (Parrot SA, USA). The sensor captured images corresponding to four separate bands: red (660 BP 40), green (550 BP 40), red edge (735 BP 10) and near-infrared (790 BP 40). For image capture at the study site, the eBee was flown at a minimum height of 107 m and a maximum height of 143 m, obtaining an image resolution of 10-14 cm per pixel. The flight plans were programmed and monitored using eMotion2 software (Sensefly, Cheseaux-Lausanne, Switzerland). The eMotion 2 software uses publicly available digital elevation data from Google Earth to develop flight plans. Previews of aerial photographs and digital surface models were generated in real time, however, full data processing took several hours. The UAV was flown at a default speed of 15 m/s that changed according to the wind direction and speed. The average area covered by a single flight was 60 ha with an image overlap of 60 - 70%. Flights were conducted in November 2016. The images were processed using Pix4D (Pix4D SA, Lausanne, Switzerland) to construct 4 band orthomosaic TIF files for each area undergoing restoration since 2014, 2010, 2006 and 2002. The processing included adjustment of the image reflectance based on the calibration panel images pre- and post-flight. Additionally, an aggregation factor of 100 was applied to the resulting images by estimating the mean of pixel intensity.

6.2.6 Data analysis

Computation of vegetation indices and textural attributes

Maps of vegetation indices were calculated using the multispectral aerial images. For calculation and extraction of values, the R packages *rgdal, raster* and *rgeos* were used. The indices (Table 6.1) were categorized as indicated by Schumacher et al. (2016): (i) single bands that represent reflectance values within the spectral range, (ii) band ratios that detect differences in surface properties, (iii) broadband greenness vegetation indices that measure photosynthetic activity, (iv) red-edge indices that exhibited high sensitivity to detect the state of vegetation, (v) soil-adjusted vegetation indices that minimize the effect of soil background, and (vi) textural attributes of the multispectral image.

Table 6.1. Equations for vegetation indices used in this study.

Index	**Formula**	**Reference**
i. Single bands of multispectral image		
Near Infrared (ρ_{NIR}), Green (ρ_G), R (ρ_R), Red-edge (ρ_{RE})		
ii. Band ratios		
Simple ratio	$\frac{\rho_{NIR}}{\rho_R}$	(Crippen 1990)
NIR Green ratio	$\frac{\rho_{NIR}}{\rho_G}$	(Haboudane et al. 2004)
iii. Broadband greenness		
Green Chlorophyll Index	$Cl_G = \frac{\rho_{NIR}}{\rho_G} - 1$	(Viña et al. 2011)
Green Normalized Difference Vegetation Index	$GNDVI = \frac{\rho_{NIR}-\rho_G}{\rho_{NIR}+\rho_G}$	(Gitelson, Merzlyak 1998)
Normalized Difference Vegetation Index	$NDVI = \frac{\rho_{NIR}-\rho_R}{\rho_{NIR}+\rho_R}$	(Carlson, Ripley 1997)
Modified Simple Ratio	$MSR = \frac{\left(\frac{\rho_{NIR}}{\rho_R}\right)-1}{\left(\sqrt{\frac{\rho_{NIR}}{\rho_R}}\right)+1}$	(Chen 1996)

Index	**Formula**	**Reference**
Non-Linear Index	$NLI = \frac{{\rho_{NIR}}^2 - \rho_R}{{\rho_{NIR}}^2 + \rho_R}$	(Goel, Qin 1994)
Green Red Vegetation Index	$GRVI = \frac{\rho_G - \rho_R}{\rho_G + \rho_R}$	(Motohka et al. 2010)
Transformed Difference Vegetation Index	$TDVI = \sqrt{0.5 + \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R}}$	(Bannari et al. 2002)
iv. Red edge indices		
Browning reflectance index	$BRI = \frac{\frac{1}{\rho_G} - \frac{1}{\rho_{RE}}}{\rho_{NIR}}$	(Merzlyak et al. 2003)
Canopy chlorophyll content index	$CCCI = \frac{\frac{\rho_{NIR} - \rho_{RE}}{\rho_{NIR} + \rho_{RE}}}{\frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R}}$	(Fitzgerald et al. 2010)
Normalized difference Near-Infrared red edge	$NDNIRRE = \frac{\rho_{NIR} - \rho_{RE}}{\rho_{NIR} + \rho_{RE}}$	(Elvidge, Chen 1995)
Normalized Difference Red Edge Red	$NDRE = \frac{\rho_{RE} - \rho_R}{\rho_{RE} + \rho_R}$	(Danson, Plummer 1995)
v. Soil adjusted vegetation indices		
Soil adjusted vegetation index	$SAVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R + 0.5} * 1.5$	(Huete 1988)
Tasseled cap Soil brightness Index	$TCSBI = 0.332 * \rho_G + 0.603 * \rho_R + 0.675 * \rho_{RE} - 0.262 * \rho_{NIR}$	(Crist, Cicone 1984)
vi. Texture attributes		
Texture attributes	Mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment, correlation	(Kavitha et al. 2011)

The texture analysis was performed using the gray-level co-occurrence matrix (GLCM), a statistical method that considers the spatial relationship of pixels. It characterizes the texture of an image by calculating how often pairs of pixels with specific values and in a specified spatial relationship occur in an image (Kim et al. 2011). The filter window size was kept low (3x3 pixels) to avoid the loss of spatial information due to over-smoothing of textural variations (Schumacher et al. 2016). For the calculation of the GLCM and the statistics (mean, variance, homogeneity, contrast, dissimilarity, entropy, second moment, correlation), the R package *glcm* was used (Zvoleff 2015).

Modeling aboveground biomass and species diversity

The Random Forest (RF) machine learning algorithm was used to develop decision-tree models predicting the biomass and species diversity from descriptors. The algorithm consists of a collection of tree-structured classifiers that determine how the input is related to a predictor variable. It is a widely used ensemble approach to feature selections for a small number of samples and large input features. Random Forest creates many regression trees (500 trees were created for this study) containing a bootstrap sample of the records with the same number of cases as the original data by using a randomly selected subset of the predictor variables. The final prediction is the average of the values predicted by all previous trees (Corona-Núñez et al. 2017). This method generates robust predictions while being insensitive to outliers and noise in comparison to single predictors (Tian et al. 2017).

Predictors were classified in several predictor sets (Schumacher et al. 2016; Table 6.1): (i) single bands, (ii) band ratios, (iii) broadband greenness indices, (iv) red-edge indices, (v) soil adjusted vegetation indices, and (vi) texture attributes. Missing values were imputed using data proximity from the RF model. The increase in training sample size can help to improve prediction accuracies (Xu et al. 2016). For this reason, for model training and parameter tuning, bootstrap resampling methods were used due to their suitability for parameter estimation with a small sample size (Banjanovic and Osborne 2016). Model performance was assessed through the estimation of mean absolute error (MAE), root mean square error (RSME) and correlation between observed and predicted values (R^2), and their standard deviation. Variable importance was evaluated using a model-based approach in which the prediction error on the out-of-bag portion of the data is recorded by means of error rate for classification and mean squared error (MSE) for regression, and the same is done after permuting each predictor variable. The second measure for variable importance is the total decrease in node impurities from splitting on the variable (Gini index for classification and residual sum of squares (RSS) for regression) (Liaw and Wiener 2002). Based on model performance, the best combination of predictors was used to map the aboveground biomass and species diversity for the study areas.

For model training and cross-validation, the R package *caret* was used (Kuhn 2008). For evaluation of variable importance and prediction, the R package *randomForest* was used (Liaw and Wiener 2002). For the creation of raster predictions, the R package *raster* was used (Hijmans and van Etten 2012). For visualization of raster predictions, the R package *ggmap* was used (Kahle and Wickham 2013).

6.3 Results

6.3.1 Measured and calculated parameters

Height, diameter and wood density were used to estimate aboveground biomass of the trees with the use of the allometric equation developed by Chave et al. (2014). The most abundant species in the area selected for ground measurements were found to be *Acacia mangium*, *Cecropia peltata*, *Casearia* sp. and *Vismia* sp. (Figure 6.3).

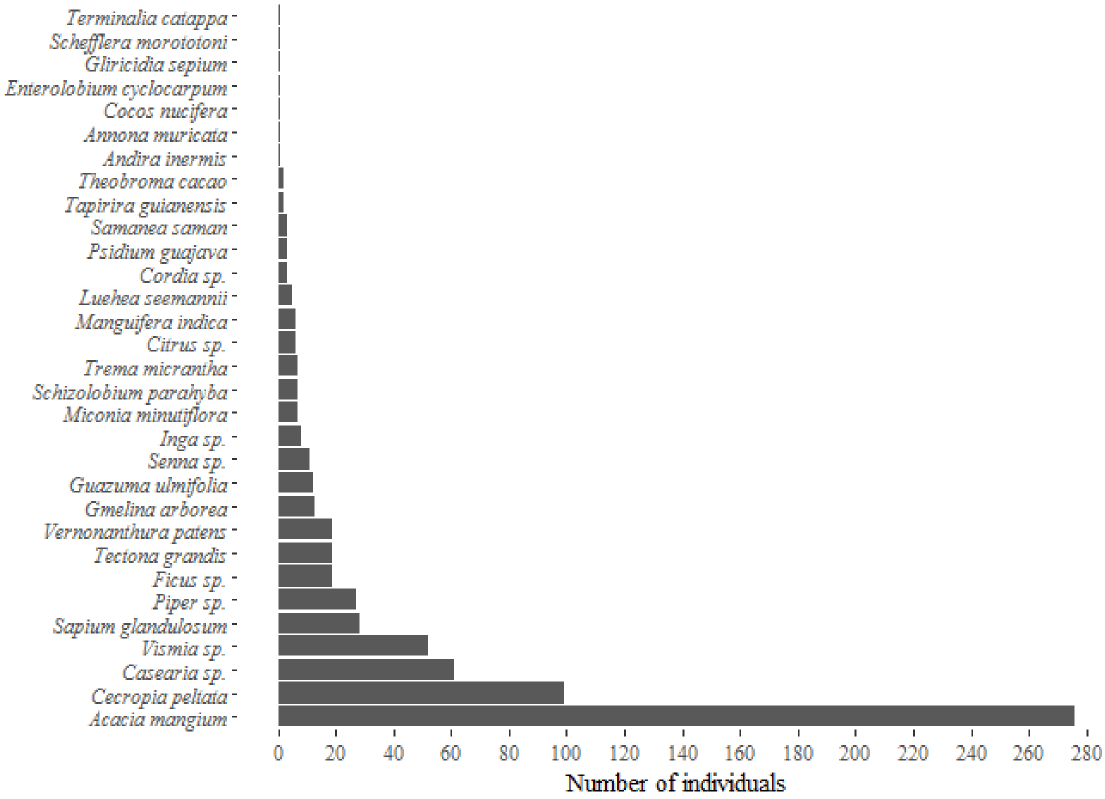

Figure 6.3. Abundance of individuals per species in sampled forest stands.

Table 6.2 shows the mean and standard deviation of structural parameters of measured trees for the most abundant species found in the area. *Acacia mangium* and *C. peltata* are the tallest and most abundant trees in the area and also exhibit higher diameter values. In comparison to *A. mangium* and *C. peltata, Casearia* sp. and *Vismia* sp. are relatively smaller. In terms of wood density, *A. mangium* exhibits higher values than the other most abundant species. *Cecropia peltata* exhibits the lowest wood density values among the other most abundant species. *Acacia mangium* had the highest values of tree biomass per individual.

Table 6.2. Parameters of the most abundant species measured in forest stands (median values).

Structural parameter	***Acacia mangium***	***Cecropia peltata***	***Casearia* sp.**	***Vismia* sp.**
Number of measured trees	277	99	61	52
Height (m)	14.7	13.2	5.9	8.3
Diameter at breast height (cm)	19	14.5	4.4	7.1
Wood density (g/cm^3)	0.59	0.32	0.41	0.51
Aboveground biomass (ton/individual)	0.09	0.04	0.003	0.01

Table 6.3 shows median values of aboveground biomass for tree and herbaceous biomass in the restoration areas. Tree biomass per hectare in the restoration areas established in 2006 and 2002 was almost 100 % higher than the values observed for the 2010 and 2014 areas. However, tree biomass of the 2010 restoration area is lower than that of the area established in 2014. Areal herbaceous biomass does not vary significantly among the areas, and there is no significant increase in herbaceous biomass in the 2010 and 2014 areas.

Tree species diversity was assessed through the calculation of the Shannon, Simpson and Fischer indices as well as species richness (Table 6.3). The median Shannon index is higher for the areas established in 2014, followed by the plot established in 2010. The lowest median Shannon index is for the plot established in 2006. A similar behavior is observed for the Simpson and Fischer indices, which exhibit highest values in the plots established in 2014 and 2010, and lowest in the plot established in 2006. The highest median values of species richness were observed in the plots established in 2014 and 2002.

6.3.2 Biomass and species diversity modeling

Random forest (RF) achieved limited performance for the estimation of herbaceous biomass (Table 6.4) evidenced by the low correlation between predicted and observed values (R^2) of 0.23. Although the model exhibited relatively low mean absolute errors, the fact that the root-mean-square error (RMSE) is equal to the standard deviation of the observed values also confirms the low predictive capacity of the model.

Table 6.3. Aboveground biomass for restoration areas based on median values. N = number of plots.

Year of establishment	**Aboveground biomass**		**Tree species diversity**			
	Tree biomass (ton/ha)	**Herbaceous biomass (ton/ha)**	**Shannon index**	**Simpson index**	**Fischer index**	**Species richness**
2014	83.4 (N = 2)	3.8 (N = 30)	1.57	0.75	2.88	7
2010	50.6 (N = 2)	4.2 (N = 30)	1.27	0.66	1.75	5
2006	121.3 (N = 6)	3.7 (N = 31)	0.18	0.08	0.44	2
2002	142.4 (N = 11)	2.9 (N = 30)	1.24	0.62	1.58	7

Table 6.4. Performance of Random Forest (RF) model for estimation of aboveground biomass and classification of vegetation cover assessed through cross-validation. Standard deviation for comparison.

Parameter	**Performance**
Herbaceous biomass per plot	
Standard deviation (ton/ha)	0.002
MAE (ton/ha)	0.001 (1.5e-4)
RMSE (ton/ha)	0.002 (4e-4)
R^2	0.23 (0.10)
R (Pearson)	0.47
Tree biomass per plot	
Standard deviation (ton/ha)	85.9
MAE (ton/ha)	52.44 (19.58)
RMSE (ton/ha)	70.61 (28.35)
R^2	0.43 (0.15)

Parameter	**Performance**
R (Pearson)	0.65
Classification herbaceous/tree	
Accuracy	0.99
Kappa	0.97

Performance values are reported as mean (standard deviation)

The model performance is higher for the estimation of areal tree biomass. The best performance of the model was achieved when all the predictors were included (Table 6.1). This was analyzed through cross-validation for predictor selection with a sequentially reduced number of predictors for the prediction of herbaceous and tree biomass, and species diversity (Figure 6.4). The model that included all predictors showed higher correlations between measured values and predictions on cross-validated test sets. An increase in correlation between observed and predicted values to 0.43 (R^2) and 0.65 for Pearson correlation indicates an improved predictive capability of the model. Additionally, RMSE values are lower than the standard deviation of the observed tree biomass values, which also confirms an increased predictive capacity of the model for tree biomass.

The RF model exhibits high accuracy for the classification of vegetation type between the categories herbaceous and forest. As the model was run with a lower percentage of samples classified as forest compared to samples classified as herbaceous, the Cohen's Kappa statistic was calculated through cross-validation for the classification model, as this can improve the quality of its performance (Ben-David 2008). High Kappa values and high accuracy of the classification model show high performance of the classifiers selected for the model, as the instances classified by the model matched most of the labeled data.

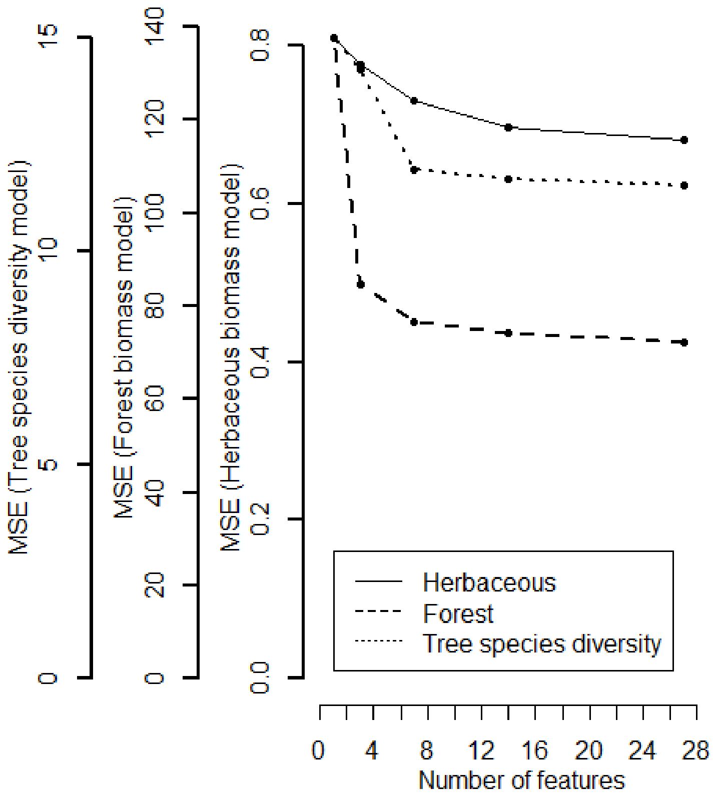

Figure 6.4. Cross-validated prediction performance of models measured by mean squared error (MSE) with a sequentially reduced number of predictors (features ranked by variable importance) via a nested cross-validation procedure.

For prediction of tree species diversity measured by biodiversity indices (Shannon, Simpson, Fischer and species richness), RF showed limited performance for the prediction of Simpson and Fischer biodiversity indices, which was confirmed by the low correlation between predicted and observed values (Table 6.5). In addition, RMSE values are higher than the standard deviation of the observed values for the prediction of Simpson and Fischer indices. However, the predictive capacity of the model improved for Shannon index and species richness. Higher correlation values between predicted and observed values can be observed for Shannon index (R^2 = 0.42) and species richness (R^2 = 0.44), as well as higher Pearson correlation values. Furthermore, RMSE values for the estimation of Shannon index and species richness are consistently lower than the standard deviation of the observed values.

Table 6.5. Random Forest (RF) model performance in predicting tree species richness assessed through cross-validation. Standard deviation for comparison.

Performance measurement	**Biodiversity index**			
	Shannon	**Simpson**	**Fischer**	**Species richness**
Standard deviation	0.71	0.31	1.61	3.05
MAE	0.55 (0.11)	0.28 (0.07)	1.79 (0.29)	3.15 (0.52)
RMSE	0.63 (0.12)	0.33 (0.06)	1.84 (0.21)	2.79 (0.53)
R^2	0.42 (0.16)	0.14 (0.12)	0.26 (0.20)	0.44 (0.19)
R (Pearson)	0.65	0.37	0.51	0.66

Performance values as mean (standard deviation)

6.3.3 Variable importance

Importance scores of each predictor generated for the RF model for estimation of herbaceous and tree biomass, species diversity and vegetation type classification (forest/herbaceous) are presented in Figure 6.5. For the classification model used to estimate class probabilities for herbaceous/forest cover, predictors such as intensity of red, near infrared (NIR) and red-edge bands had higher importance, as well as the Simple Ratio (SR) vegetation index. Furthermore, the red-edge indices Normalized Difference Near-Infrared red edge (NDNIRRE) and canopy chlorophyll content index (CCCI) exhibited relatively higher importance for the classification of vegetation type.

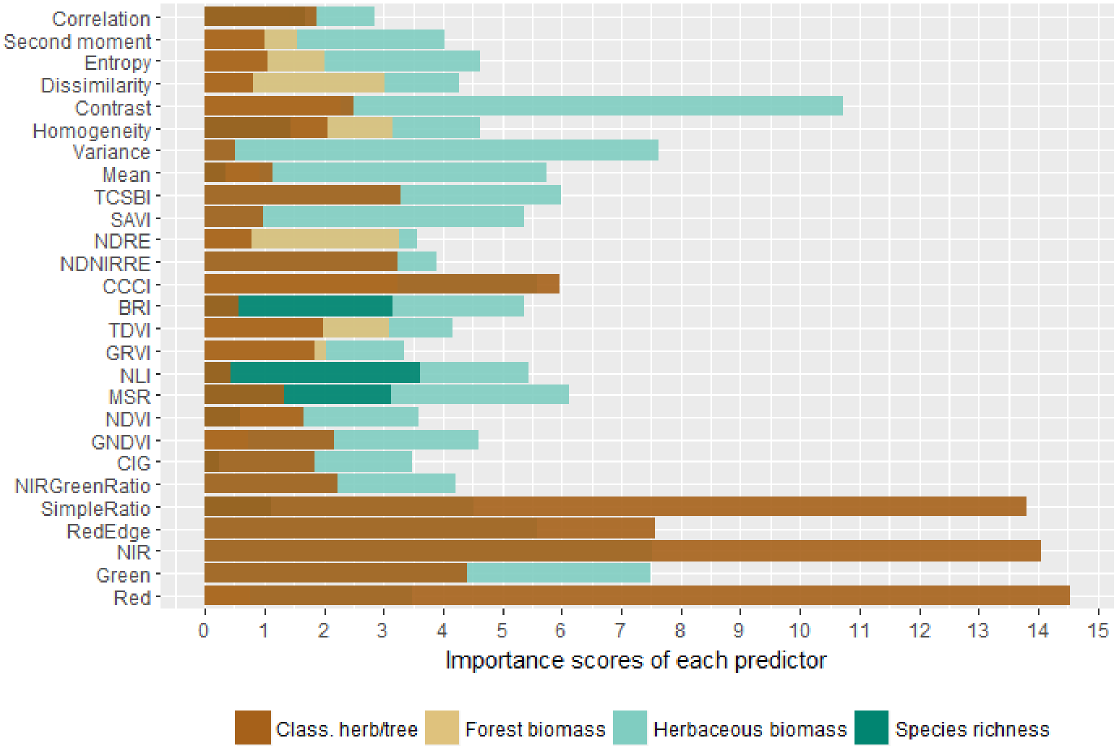

Figure 6.5. Importance scores for predictors used in Random Forest model for vegetation type classification, herbaceous and forest biomass estimation, and tree species diversity based on permutation of predictor variables for accuracy estimation.[§]

The most important predictors of tree species diversity are found to be the Transformed Difference Vegetation Index (TDVI) and the Browning reflectance index (BRI). A textural band of the multispectral image, i.e. variance, also has relatively high importance as a predictor in this model.

For the estimation of herbaceous biomass, the most important predictors were the textural bands of the multispectral image, i.e. contrast (9.71), variance (7.27), mean (5.97), and dissimilarity (5.77). The Browning reflectance index (BRI) also exhibited a relatively high importance (6.84) as a predictor. For the estimation of tree biomass, the most important predictor was a textural band of the multispectral image, i.e. homogeneity (4.26). The second most important predictor was the red-edge index NDRE

[§] Refer to Table 6.1 for the meaning of abbreviations.

with a score of 4.07. The green-red vegetation index was the third most important predictor in this model (3.41). The fourth was a textural band, i.e. correlation of the multispectral image (2.50).

6.3.4 Prediction maps

Tree biomass

Prediction maps were created with RF for the tree biomass maps (Figure 6.6) obtained with the best performing model (all predictors included; Table 6.1; $R^2 = 0.43$, Pearson correlation = 0.65, RSME = 70.61 tons/ha). No prediction maps were created for herbaceous biomass due to the low predictive capability observed for the RF model. Predicted values for tree biomass were between 120 and 180 tons/ha for the restoration areas established in 2014, 2010 and 2006, and between 160 and 240 tons/ha for the area established in 2002. The highest predicted value of approximately 180 tons/ha for the restoration areas established in 2014 and 2006 is similar to the maximum value observed in the field (183 tons/ha) for the restoration area established in 2006, but much higher than that observed in the restoration area established in 2014 (104 tons/ha). The predicted value 240 tons/ha for the restoration area established in 2002 is similar to the maximum value observed in the field (246 tons/ha). However, for the restoration area established in 2010, the model highly overestimated the tree biomass value with approximately 180 tons/ha given that the maximum observed value in the field was 53 tons/ha.

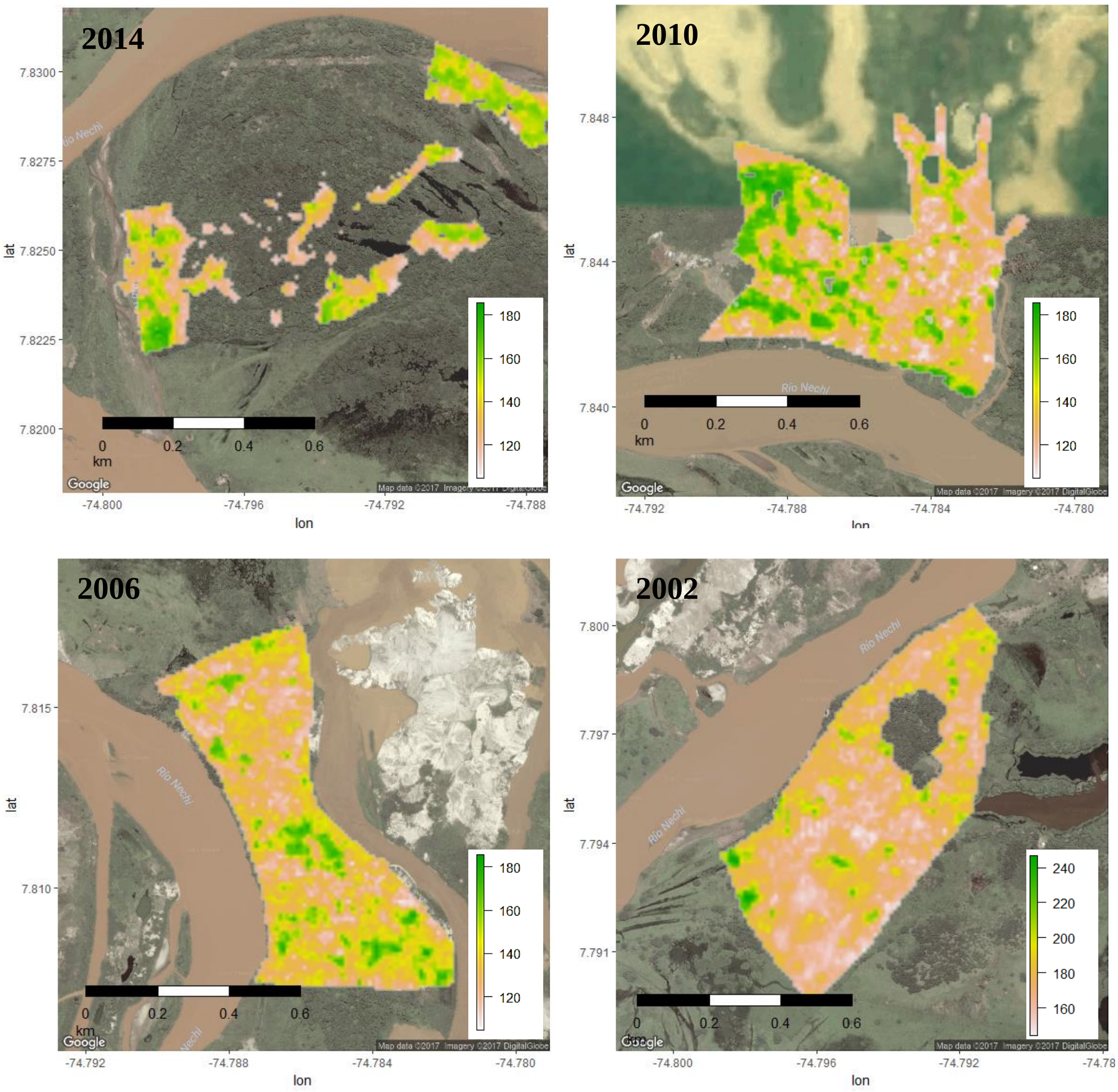

Figure 6.6. Forest aboveground biomass (tons/ha) estimated with Random Forest model (all predictors included (Table 6.1), $R^2 = 0.43$, Pearson correlation = 0.65, RSME = 70.61 tons/ha).

Tree biomass estimations for the restoration area established in 2014 are scattered on only small areas of the plot, where the model identified areas with bare soil and predicted no tree biomass. In such older restoration plots, tree biomass is mainly scattered over the plots, tending to decrease towards the edges. However, the model tended to overestimate, since median values measured in the field (Table 6.3) were much lower than the values predicted by the model. Furthermore, the prediction maps show that tree biomass distribution is not homogeneous on these plots, which corresponds to the field observations where tree biomass does not follow a clear distribution pattern.

Tree species richness

A map of predicted tree species richness was created for the four restoration areas with the best performing model (all predictors included; Table 6.1; $R^2 = 0.44$, Pearson correlation = 0.66, RSME = 2.79). Tree species richness was selected for prediction as the RF model had better predictive capability when it was used as a response variable. Predicted species richness ranked between 4.5 and 7 for the restoration area established in 2014, between 3.5 and 5.5 for that established in 2010, between 3.5 and 6 for that established in 2006, and between 4 and 8 for the area established in 2002. Minimum and maximum values predicted for the restoration areas established in 2014 and 2010 are similar to the range observed in the field (2014: 5-8 species, 2010: 4-6 species). For the restoration area established in 2006, the maximum value (8 species) coincides with the value observed in the field, however, the minimum value (1 species) was overestimated. For the restoration area established in 2002, the range of species richness observed in the field (1-11 species) was broader than that predicted by the model (4-8).

For the restoration area established in 2014, the species richness predictions were only performed in small areas of the plot as done for tree biomass. This is because the species richness model recognized the areas with bare soil, therefore blank areas correspond to the zero values predicted by the RF model. When comparing the maps of predicted species richness (Figure 6.7) and the maps of predicted tree biomass (Figure 6.6), it can be seen that areas with higher species richness do not necessarily correspond to areas with higher tree biomass. Furthermore, areas with predicted higher species richness are highly scattered and do not follow a spatial pattern.

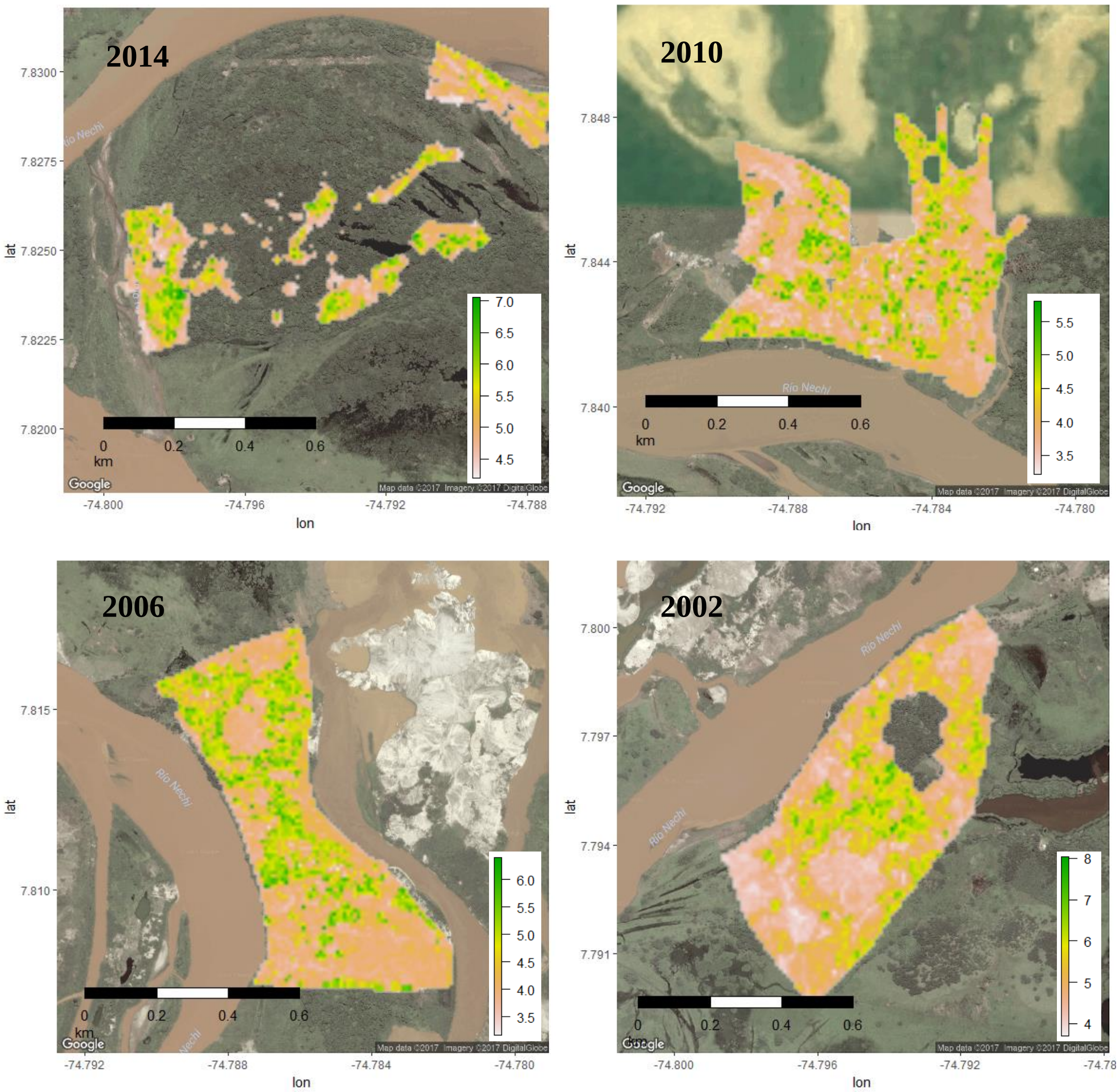

Figure 6.7. Species richness estimated with Random Forest model (all predictors included; Table 6.1; $R^2 = 0.44$, Pearson correlation = 0.66, RSME = 2.79).

Vegetation type classification

The RF model exhibited very high predictive capability for the classification of vegetation type between the categories tree cover and herbaceous cover. Maps of predicted class probabilities were created for the four restoration areas (Figure 6.8). The values depicted in this map represent for each pixel the probability of a herbaceous cover. Therefore, a probability 1 means with a confidence of 95% that the pixel corresponds to herbaceous vegetation. Lower probability values for herbaceous cover indicate an increasing probability of the pixels depicting forest cover.

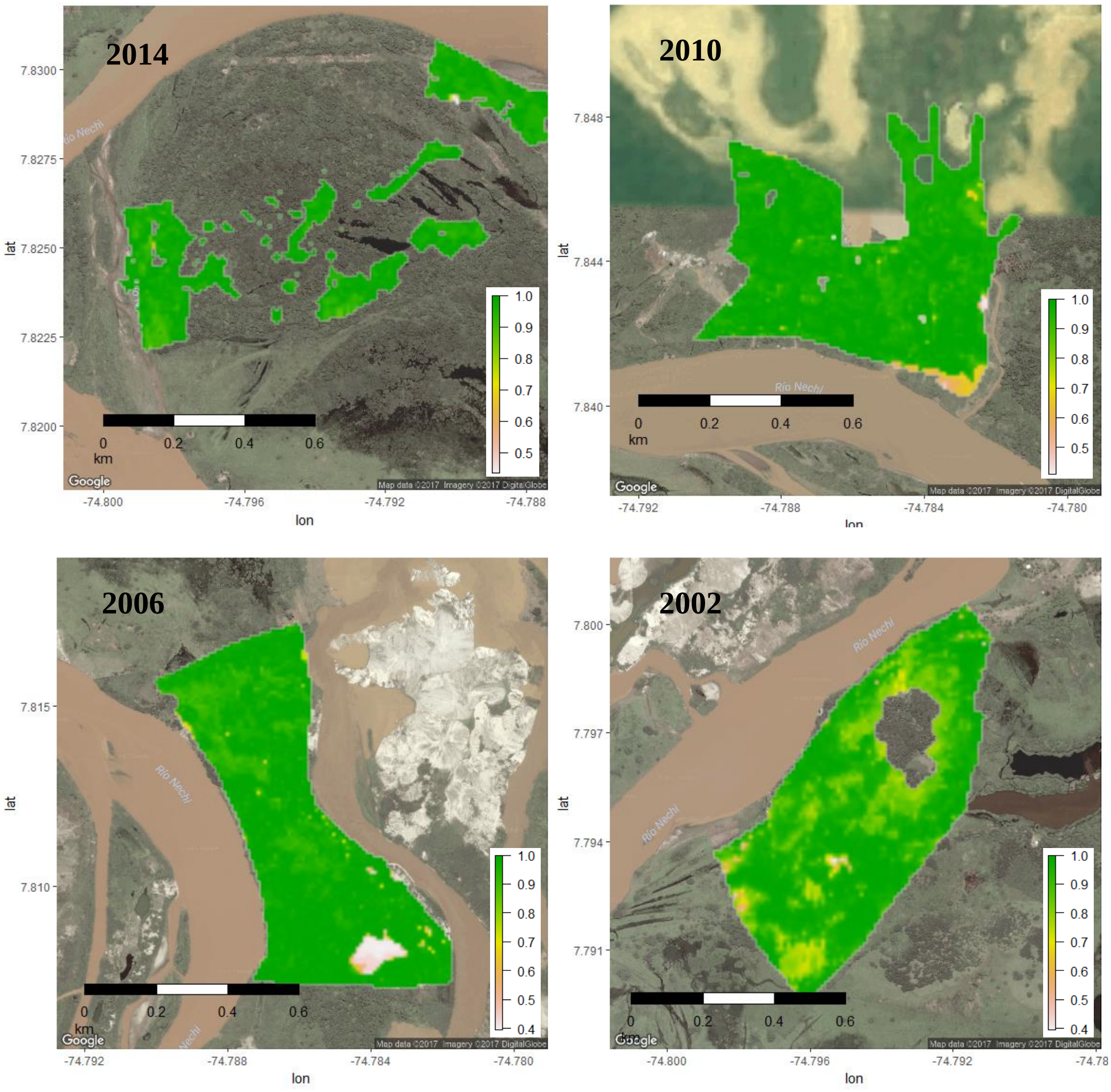

Figure 6.8. Herbaceous/forest cover probabilities estimated with Random Forest model (all predictors included; Table 6.1; accuracy = 0.99, Kappa = 0.97)

For the restoration area established in 2014, the model also identified areas with bare soil and did not assign a classification to these. For the classified areas, the model estimated that most of them were covered by herbaceous biomass, with only small areas that could potentially be forest cover. The map for the restoration areas established in 2010 and 2006 shows many scattered spots that have a higher probability of being classified as forest cover, however, most of the area was classified as herbaceous biomass. The map of the area established in 2002 shows much larger areas with higher probability of depicting forest cover. When comparing the maps of predicted class probabilities (Figure 6.8) and the maps of predicted tree biomass (Figure 6.6), it can be seen that the class probabilities roughly follow the same pattern, i.e. areas with higher tree biomass roughly corresponding to areas with a lower probability of being classified as herbaceous cover. Once more, there is not a clear pattern for the distribution of these classes, while predicted forest cover is randomly distributed within the restoration areas.

6.4 Discussion

6.4.1 Implications of the use of UAV and high-resolution images

Revegetation management requires an understanding of patterns of vegetation in a timely and accurate manner to make informed decisions. Therefore, the development of a cost-effective and accurate method to acquire forest attributes is essential to management and restoration activities. Here, the use of UAVs represents an opportunity to land managers (Mohan et al., 2017). Multispectral images captured with a Sensefly UAV proved useful to estimate tree biomass and species richness in areas covered by gold mining waste undergoing restoration through agroforestry. Therefore, the methodology used for this study has the potential to be an effective and affordable approach to support the reclamation processes being conducted in gold mining areas. UAVs are especially useful for plot-level assessments in the field, as they can capture highly specific spectral traits at the high spatial resolution and with the desired temporal frequencies (Zahawi et al., 2015). Furthermore, the fact that repeated flights could be conducted over the same plots with varying flight paths resulted in better quality coverage, therefore maximizing line crossings and multiple flights should be considered (Brede et al., 2017). However, the flight time of UAVs is very short (approximately 15 minutes), hence each flight results in a relatively small documented area. Flying the UAV at higher altitude can help to compensate for this limitation, but it could be detrimental to the overall accuracy with respect to the resolution of the images (Mohan et al., 2017). Furthermore, the use of UAVs is favorable in terms of operability and accessibility given that data can be collected whenever is required (Li et al., 2016).

6.4.2 Tree and herbaceous biomass modeling

In spite of the fact that spectral predictors and broadband greenness vegetation indices improved herbaceous biomass estimates using the RF model in the plots with low to medium herbaceous biomass (Greaves et al., 2016), a low predictive capacity of the model was observed. This may be because the approach used in this study aimed to aggregate structural information of vegetation from predefined grids within herbaceous biomass plots measuring 4 m^2. This aggregation process generates the risk of confusion with respect to a decision tree within the RF model when different vegetation composition exhibits similar signals. This may explain the low performance of the model for the prediction of herbaceous biomass as was also found by Anderson et al. (2018). Moreover, shrub vegetation is not dense enough to cover the ground, thus the soil can have important effects on the spectral signature (Feng et al., 2017).

The results indicate that the predictors for estimating forest aboveground biomass by the RF model in order of decreasing importance are textural variables (homogeneity, correlation, contrast, entropy and dissimilarity), red-edge indices (NDRE, CCI), broadband greenness indices (GRVI) and band ratios (NIR green ratio). Single bands and band ratios have been identified as good predictors for tree biomass by several studies (Liu, 2016; Galidaki et al., 2017; Adam et al., 2014; Meyer et al., 2017), and the combination with texture features of the image results are favorable for addressing existing problems with vegetation index saturation and data acquisition for mapping tree biomass (López-Serrano et al., 2016). Model prediction improvements when adding texture layers have been observed in several studies (Xu et al., 2016; Bastin et al., 2014; Cutler et al., 2012; Eckert, 2012), as texture analysis brings additional spatial information for estimating the forest structure from the knowledge of surrounding pixels.

Furthermore, a large part of spatial dependence at a short distance is explained by the texture layers included in the model (Xu et al., 2016).

Kachamba et al. (2016) emphasized the importance of incorporating the spectral components of UAV point clouds, as they present useful information to estimate biomass. In this study, red-edge indices were important predictors for both tree biomass and classification of vegetation type. In arid regions, red-edge vegetation indices have been better estimators of green vegetation fraction than broadband greenness vegetation indices (Li et al., 2012). Schumacher et al. (2016) also demonstrated that texture attributes and red-edge indices improve the predictive performance of RF models for tree biomass estimation in semi-arid regions in comparison to conventional methods limited only to broadband vegetation indices.

6.4.3 Species diversity modeling

Mapping diversity estimates are accomplished by analyzing the variation of spectral signals and correlating the variation with measures of plant diversity (Gould, 2000). Therefore, the analysis of optical diversity can show good correlation with species richness and evenness estimated by Shannon index (Wang et al., 2016). This was observed in the present study. The results indicate that the predictors for estimating species richness by the RF model in order of decreasing importance are broadband greenness indices (TDVI, GRVI), red-edge indices (BRI), texture attributes (variance, correlation), band ratios (NIR green ratio), and single bands (red edge, green, red). Texture statistics and vegetation indices derived from the NIR band are good predictors of species richness of trees and are able to detect local changes in habitat structures (Wallis et al., 2017).

The fact that variance (textural attribute) was one of the most important predictors of species richness is in agreement with the findings presented by Wang et al. (2016), who studied coefficient of variation as a metric of optical diversity and found that it significantly correlated with conventional species diversity indices (richness and

Shannon index). However, in this study broadband greenness and red-edge indices had higher importance scores as predictors of species richness. This can be attributed to the fact that higher tree species richness might occur in areas where the canopy is higher and denser, therefore pigment-related spectral data are more important predictors of tree species richness than heterogeneity measurements assessed with texture metrics (Wallis et al., 2017). Madonsela et al. (2017) also found significant linear relationships between vegetation indices (NDVI and simple ratio) and measures of local tree diversity, but unlike in the present study, found that textural attributes had not shown significant relationships with tree species diversity.

6.4.4 Model uncertainties and limitations

Estimation of aboveground biomass is a complex procedure that requires careful design of each step, i.e. (i) calculation of aboveground biomass from sample plots, (ii) extraction and selection of remote sensing variables, (iii) selection of modeling, and (iv) evaluation of prediction results (Lu et al., 2016). The calculation of aboveground biomass from sample plots using allometric models is usually a critical step resulting in uncertainty of biomass estimation, especially in moist tropical areas where the complex species composition and the difficulty of selecting an allometric equation for specific tree species result in high uncertainty in the aboveground reference data (Feng et al., 2017). It is expected that the relationship between remotely sensed spectral data and aboveground biomass is species dependent (Chen et al., 2016). However, the model in this study was developed at plot level where the average relationship for tree species within plots was modeled, which might not completely capture the variations within agroforestry fields (Feng et al., 2017).

Modeling vegetation biomass on an area rather than on a plant basis is valuable when the measurements consider all vegetation within a plot and none outside this plot (Anderson et al., 2018) as was the case of this study. Previous studies have shown that a combination of multiple predictor variables such as vegetation indices can improve the estimation accuracy of vegetation parameters (Li et al., 2016). Due to the high heterogeneity in the distribution of vegetation in the studied areas undergoing reclamation, where vegetation communities with low biomass are widespread in the landscape, a model including several predictor variables is the most suitable option for prediction of vegetation features in terms of improved accuracy (Greaves et al., 2016). Previous studies that have compared the performance of the RF model versus other machine learning algorithms such as k-Nearest Neighbors (kNN) or parametric methods such as multiple linear regression (MLR) have shown that RF is a more robust technique for biomass predictions (López-Serrano et al., 2016). Shadowing within and between tree crowns influences canopy reflectance, texture complexity, tree species variety, and image quality, and can also affect the predictive capacity of the model (Mohan et al., 2017). Furthermore, environmental factors such as wind speed, fog and temperature variations can interfere in the process of image capturing by the UAV, which should be addressed for remote sensing of vegetation structures (Zarco-Tejada et al., 2014).

GPS errors associated with tree location estimation are also a common source of uncertainty that needs further investigation (Mohan et al., 2017). The small discrepancies in values extracted from the multispectral images versus ground-truth values may have introduced some erroneous biomass and species richness values, especially when a relatively large amount of vegetation could have been either wrongly included or excluded. Furthermore, the predictive capacity of the model improved after applying an aggregation factor of 100 to the multispectral images. Greaves et al. (2016) also observed an increased predictive capability of a RF model using broadband greenness vegetation indices for biomass estimation using a coarser resolution, which can be attributed to georeferencing errors occurring during field measurements.

6.4.5 Implications for the areas undergoing restoration

The spatial distribution pattern of vegetation is an indicator of the success of restoration programs in disturbed sites. For instance, the presence of shrubs represents the regeneration capacity and reflects the reproduction ability of a created ecosystem, while trees (DBH > 10 cm) reflect the survival capacity of vegetation in restored ecosystems (Juwarkar and Singh, 2016). For this study, in the younger restoration areas, vegetation growth is mainly in the form of pioneer shrubs with a few scattered areas that have preserved the pre-disturbance vegetation cover. In terms of succession, there is clear evidence of reclamation success, as even in the relatively young area established in 2010, there are only a few scattered areas without vegetation cover. Furthermore, in older areas undergoing vegetation since 2002 and 2006, there were no signs of bare soil that could indicate a possible reverse succession.

There is a broad perception that productivity integrates major drivers of tree species diversity, which can include land use, climate, and biotic change, however, productivity itself cannot directly assess tree species diversity (Sala et al., 2000). Another finding of this study is the fact that older reclamation areas do not have significantly higher species richness than younger reclamation areas. Murguía et al. (2016) emphasize the fact that large-scale metal mining activities exert pressure on biodiversity by adversely changing habitats at local and regional scales. Therefore, it should be considered that successful restoration of the post-mining landscape should also include tree species diversity restoration. Consequently, reclamation practices ought to focus on becoming a source of germplasm for various species, which might improve the environmental and economic conditions of the local area (Juwarkar and Singh, 2016).

Some studies show that high tree species diversity is associated with higher biomass (Cardinale et al., 2007). On the other hand, recent studies suggest that there could be a decline in diversity at high productivity (Fraser et al., 2015). The humped-back model proposed by Fraser et al. (2015) suggests that "plant diversity peaks at intermediate productivity; at low productivity few species can tolerate the environmental stresses, and at high productivity a few highly competitive species dominate". The comparison of spatial patterns of biomass and species richness in the research area show that areas with high biomass do not necessarily coincide with areas with higher species richness. This may be due to the fact that *Acacia mangium* became a dominant species due to its strong adaptability and resistance as well as its rapid growth (Chazdon, 2008) and has played an important role in the restoration of vegetation cover in this area. However, its invasiveness in disturbed ecosystems has been documented (Osunkoya et al., 2005), as it tends to convert the habitats to nearly monospecific stands over time.

The capacity of agroforestry systems to provide food, shelter, habitat and resources for multiple species is highly context dependent. Agroforestry systems tend to have less diversity than forest but higher diversity than traditional agriculture, however, this is highly conditioned to management practices that improve (or not) resilience of the created ecosystems (Torralba et al., 2016). For instance, in repeated cropping cycles with shortening fallow phases, a point will be reached at which tree regeneration fails completely, and the systems will move to the grassland domain (Norgrove and Beck, 2016). In this regard, Jakovac et al. (2015) found that the recovery of forest structure is determined by management intensity, while the recovery of tree species diversity is driven by landscape configuration. Therefore, special attention should be paid to secondary forests that develop during the fallow period, as the sustainability of agroforestry systems may highly depend on them.

Given that the disturbance and recovery history of a mining site can be highly complex, especially when measured over long time periods, having the spatial knowledge of the disturbance agent may improve predictions of aboveground biomass (Pflugmacher et al., 2014). Post-disturbance conditions following alluvial gold mining activities are influenced largely by deposit properties, site preparation practices, the technology used for mining, and management decisions. Therefore, an analysis of the spatial heterogeneity of these deposits could also contribute to the prediction of aboveground biomass. Optical diversity and species diversity can be influenced by environmental heterogeneity such as soil texture or microtopographic variability (Zhao et al., 2015), therefore understanding the relationship between subtle gradients in soil and microtopography and optical variations can be a suitable objective for future work.

The outcome of restoration programs depends on the nature and extent of plant distribution. Vegetation cover, species diversity, and ecosystem development processes are the major indicators of restoration success (Juwarkar and Singh, 2016). In the study area, an increase in forest area could occur if forest conservation practices, combined with agricultural abandonment, take place (Hansen et al., 2013). However, this assertion strongly depends on the intended reclamation goal. Up to now, the reclamation goal of the mining company and the inhabitants of the area has been to combine trees, agricultural crops and livestock for the reestablishment of an ecologically and economically viable land-use system. Evidence that this balance can be achieved is provided by Antwi et al. (2014), who found that in a post-mining landscape, agriculture played an essential role in forest growth, and emerged as the most stable land-cover type. However, the restoration process depends on the specific characteristics of a particular ecosystem, especially in post-mining landscapes such as the type and impact of the disturbance, planted species, climatic conditions, and management (Juwarkar and Singh, 2016). Therefore, the measurement of success of a restoration process is highly specific to each site, and can hardly be compared with restoration conducted in other mining sites.

6.5 Conclusions

The results of this study suggest that areas covered by gold mining waste can be recovered and converted into productive ecosystems if appropriate management strategies are adopted. The use of remote sensing techniques using a UAV and field measurements allowed gaining information about the study area in a way that reduced error due to data interpolation or data misrepresentation given the high heterogeneity of the study area. Furthermore, the results show that UAV multispectral imagery is suitable to generate information for biomass estimation and vegetation classification. The combination of spectral data and ground-truth data using a machine learning algorithm had the ability to model high-dimensional non-linear relationships with relative robustness with respect to noise features, and allowed measuring the individual importance of several predictors.

The method applied in this study can be used for estimation of vegetation biomass with a broad range of dimensions and where vegetation classes are mixed. The analysis of the development of tree plantations and vegetation reestablishment should be oriented to increase biomass, maximize productivity, and promote an increase in tree species diversity in the areas undergoing reclamation. In addition, the tree species selection for the agroforestry systems should aim to minimize the use of invasive species, and promote the use of native species that improve the resilience of the newly created ecosystems.

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7. CONCLUSIONS AND OUTLOOK

The chapters of this dissertation cover different perspectives on agroforestry as a post-mining land-use approach in north-west Colombia. They embrace some of the land management challenges that the farmers working in areas undergoing reclamation must face to bring the areas affected by gold mining back to productivity and reinstate agricultural production systems. In the following, insights from this research are presented.

7.1 Need for suitable post-mining land-use approach in Colombia

Gold mining activities put pressure on the environment due to the high resource intensity of their operations, release of pollutants such as mercury and cyanide, and formation of dredging waste deposits on banks of rivers. This compromises the wellbeing and livelihoods of the communities in nearby areas. From the agricultural productivity perspective, the deposition of dredging waste poses a major threat, as it covers vast areas of land that were previously dedicated to agricultural activities. The deposits created by gold mining usually have low nutrient levels, acidic conditions and poor structural features that make the spontaneous reestablishment of a vegetation cover difficult.

As the global demand for gold continues to rise, the waste production associated with its exploitation will also increase. To cope with this, a suitable post-mining land-use approach needs to ensure the establishment of sustainably productive and ecologically valuable post-mining landscapes. Agroforestry may be in many respects a beneficial land-use system for marginal post-mining landscapes, as the use of crops and livestock can complement protective reforestation in affected areas. Planting of crops and cattle grazing in the more fertile areas of the waste deposits can help to reinstate the income opportunities of farmers whilst planting of woody perennials in less fertile areas of the deposits can contribute to restoring the productivity of the areas covered with waste.

7.2 Role of farmers’ knowledge

The farmers working in areas undergoing reclamation through agroforestry face major challenges with respect to developing a suitable land-management scheme that allows them to fulfill their production objectives (crops, trees and animals), and the reclamation objectives (establishment of a vegetation cover and improvement in soil fertility). The physical and chemical properties of the waste deposits make the establishment of crops difficult, and this is exacerbated by their high spatial variability and seasonal variability, susceptibility to weed invasion, and frequent pest outbreaks. To address these challenges, the farmers have developed a whole set of indicators to recognize areas suitable for crop establishment, cattle grazing or planting of woody perennials, as well as a set of practices to improve the productivity and quality of the crops. However, the development of this set of indicators and practices is a process that is mostly done by each farmer individually with the aid of extensionists of the mining company and is usually a result of years of trial and error, which causes significant loss of resources.

7.3 Insights on soil development

To minimize the loss of resources, it is necessary to gain insight on the pedological properties of the waste deposits through an in-depth analysis of their physical, chemical and hydrological properties and the changes that the waste deposits experience as a result of vegetation establishment. The chronosequence analysis of the waste deposits undergoing reclamation with agroforestry systems revealed that, on a larger scale, the main driver of variability was the type of technology used for alluvial gold mining. This determines the type of waste deposit that is going to be created in terms of structural and physical properties as well as chemical properties. A comparison between gravel deposits and sand deposits revealed structural differences but, most importantly, critical differences in the chemical composition of these two types of deposits that are present in all analyses. Therefore, these differences need to be considered when making decisions on management practices, and on the selection of crops and woody species to be planted on the different deposits.

The fact that the first restoration plots established on the waste deposits were planted in 2002 means only a relatively short time span for analysis of temporal changes in the deposits across a chronosequence of restoration. Furthermore, a critical assumption for chronosequence studies is that each site differs only in the time period since establishment and that they share the same history of biotic and abiotic components. Although the sites may be formed by similar substrates, the high inherent variability of these deposits suggests that each site can have different successional trajectories and diverse pathways of soil development.

7.4 Heterogeneity of waste deposits

The heterogeneity of waste deposits produced by alluvial gold mining is not only determined by the technology used for dredging, but also by the geochemical properties of the dredged deposits and the random mixing of the alluvial materials through dredging operations and waste depositing. A further understanding of the patterns of spatial variability of the waste deposits helps the farmers to identify areas with higher nutrient contents and better physical properties that are suitable for crop establishment, as well as to identify areas where protective reforestation is crucial to restore soil fertility. For this purpose, a geostatistical analysis was conducted to understand the spatial variability patterns of soil nutrients, textural and chemical properties of the waste deposits. The spatial variability analysis revealed that substantial changes in nutrient levels and organic matter can be observed even within small distances of less than 100 m.

The high spatial variability of the properties of waste deposits suggests that management practices, as well as the selection of crop and woody species, should take into account the highly differing nutrient and textural conditions of the deposits. Therefore, a spatial cluster analysis was conducted to delineate management zones, which were validated through the analysis of multispectral aerial images used to develop NDVI maps as a proxy of productivity. This combined analysis allows verifying that areas clustered as being more fertile had indeed higher NDVI values and, vice versa, areas clustered as less fertile had lower NDVI values. The delineation process is the first stage for implementation of site-specific management strategies. This is an adequate approach to improve the productivity of deposits as well as to reduce the wasting of resources through the identification of areas suitable for crop establishment through trial and error.

7.5 Establishment of vegetation cover

In terms of establishment of vegetation cover, there is clear evidence of a successful reclamation process. In areas undergoing reclamation over longer periods of time, there are no signs of bare soil, and even in those undergoing reclamation for short periods of time, only a few scattered areas without vegetation cover can be observed. In terms of biomass, values are higher in older restoration plots than in younger ones. However, the assessment of species richness shows that older restoration areas are not more diverse than younger ones. Also, areas with higher biomass do not coincide with areas of higher species richness. Therefore, the reclamation practices should focus not only on restoring the vegetation cover but also on creating a source of germplasm to increase species diversity, which can improve the environmental and economic conditions of the area undergoing reclamation.

To assess the recovery of vegetation cover through biomass and species richness maps, a machine learning algorithm was used to connect field measurements of biomass and species richness with multispectral images captured by a drone. In this process, sources of error can be field measurements and allometric determination of biomass, interferences in the process of image capturing, and the calculations performed for the modeling. Nevertheless, the model used for this study achieved an acceptable predictive capacity for tree biomass and species richness in the area. However, results must be interpreted with care, as the variables modeled are average relationships of biomass and species richness within plots, which might not completely capture the within-field variability.

7.6 Conclusions on the methodological approach

Soil sampling for this study was conducted under three sampling schemes: (1) based on the local knowledge of farmers who indicated fertile and non-fertile areas of their fields; (2) based on a chronosequence approach and an empirical classification of deposit types; (3) a spatial grid of sampling points. The first sampling scheme allowed to associate certain physical and chemical properties with higher agricultural productivity. This scheme also endorsed the profound knowledge that the farmers possess of their fields based on observable features of the deposits that they have perfected with experience. The second sampling scheme provided an overview of the variations in chemical properties along the chronosequence of reclamation. However the limited number of samples resulting from this scheme exacerbated by the relatively short time after vegetation establishment, did not allow to get a good overview of the actual evolution of these deposits, instead it evidenced the necessity of a more robust sampling scheme for the study of the properties of the waste deposits as the range of variability was observed to be very broad. The spatially explicit sampling scheme provided sufficient information for further stages of data analysis on spatial variability of deposit properties, which in this specific case proved to be valuable to gain insight on the actual scale of variability of the soil characteristics.

With regard to data analysis, it is worthwhile to highlight that the anthropogenic origin of these waste deposits made them characteristically heterogeneous, which needed to be well-thought-out for statistical analysis of data. Heterogeneity generally results in multimodality and therefore in non-normality. It could also result in heteroscedasticity concerning data to be compared which then also would violate assumptions of traditional statistical modeling. In addition, the methods for data analysis were selected to minimize the volatility in results caused by influential values (e.g. outliers). Therefore the shift from mean to more robust statistics (e.g. median) or the estimation of more realistic standard errors through resampling techniques (e.g. bootstrap) was a decisive step for this study. This statistical approach allowed to analyze the rather rough data to obtain more robust and comprehensive results without losing valuable information through data normalization or discretization.

The high spatial variability of the properties of the waste deposits was observed using soil mapping techniques based on the geostatistical analysis. The use of this technique allowed to visualize the variability of each soil property in distances of less than a hundred meters. Using a spatial clustering technique, the spatially explicit characterization of the soil was used to delineate homogeneous zones within the restoration areas that could be dedicated to different purposes according to their overall soil quality. This technique was then validated with vegetation indices estimated from drone images, which provided a proxy for productivity of the delineated zones. Moreover, machine learning algorithms (Random Forest, k-nearest neighbors) were used to predict the spatial distribution of tree biomass and tree species diversity based on the combination of data collected through vegetation survey and spectral indices obtained from drone images. Furthermore, the use of high-resolution remotely sensed data showed promise as a tool to assess the spatial variation in biomass and species richness, as well as to reflect the variation in soil properties and potential productivity of agricultural fields.

The methodological approach used for this research, combining soil digital mapping, aerial image analysis and machine learning algorithms lead to a set of results that were both accurate and interpretable. A methodological approach such as the one used for this study can be relevant for research in degraded or disturbed areas where agricultural activities are to be reinstated, as well as for studies conducted in areas with low agricultural productivity to address the spatial variation of soil chemical and physical characteristics and their influence on productivity. This methodology can be used to 1) determine yield-limiting factors among soil parameters within small areas of a field; 2) show the spatial variability of soil characteristics associated with crop productivity or biomass distribution; 3) delineate differential management zones to indicate which areas within the field is can be most responsive to amelioration through site-specific management of crop inputs.

7.7 Outlook

Based on the findings of this research, tasks are suggested for land managers and extensionists, as well as for future research in the area.

7.7.1 Recommendations for practitioners and extensionists

- Promote cooperation between more experienced farmers and farmers new to the area through the creation of communal demonstration areas where new farmers can collectively learn from both extensionists and more experienced farmers how to better manage and protect their land.
- Promote dialogues between farmers and scientists, and extensionists and scientists that allow complementing local knowledge with relevant scientific advice.
- Develop integrated management schemes that incorporate farmers’ perceptions and knowledge, especially in the early stages of the design of the reclamation schemes.
- Elaborate strategies to increase the acceptance of management guidelines provided by extensionists to the farmers.
- Create site-specific management schemes that allow decision making on the farmers’ fields that accounts for the inherent spatial variability of the deposits.

7.7.2 Recommendations for reclamation management

- Initial coverage with natural topsoil can support the establishment of soil ecosystem engineers such as earthworms and ants, and can play a decisive role in the development of plant communities.
- Some unfavorable soil properties can be compensated for through the application of special ameliorative measures such as the use of amendments prior to revegetation, including organic waste, compost or the use of cover crops, to buffer soil pH where necessary, improve water holding and cation exchange capacity of the substrate, establish active microbial communities, and provide nutrients to stimulate the reestablishment of vegetation. The application of amendments should consider the high spatial heterogeneity of the deposits, as the nutrient requirements may significantly differ even within areas of less than 100 m apart.
- Understanding spatial variability of areas undergoing restoration will allow an overall increased productivity by developing strategies suited to the characteristics of each field and its potential uses. In addition, areas suitable for crop establishment can be more easily identified.
- In acidic areas with low cation exchange capacity, liming would be a suitable strategy due to its neutralizing capacity and its availability in most households in the area.
- Reclamation practices should also focus on becoming a source of germplasm for various species, which might improve the environmental and economic conditions of the area. Selection of tree species for revegetation should be related to their capacity to increase soil nutrients and sequester carbon. Exclusive establishment of fast-growing trees may not be as beneficial as mixed stands in terms of tree species diversity of the areas undergoing reclamation.

7.7.3 Recommendations for future research

- Further studies need to be conducted to compare the seasonal variability of soil properties and its influence on the delineated management zones to understand the dynamics of the restoration process. In addition, crop yield should be measured in each zone to understand the agronomic significance of the delineation process. Field experiments need to be conducted for the assessment of the impact on soil properties of specific species for protective reforestation and as cover crops, as well as to assess the effect of specific soil amendments (lime, ash, compost) and management practices (green manure, cover crops) on revegetation and crop productivity.
- Analysis of the nutrient fluxes through floodwater and of how the design of the waste deposits can be improved to take better advantage of these nutrient pulses.
- The delineation of management zones should not only be based on spatial clusters of soil properties but also should include farmers' perceptions of soil fertility. For this purpose, participatory mapping can be conducted with the farmers working in the area to develop site-specific management schemes for the areas undergoing reclamation.

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