Science of the Total Environment 566–567 (2016) 761–770

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Selection of forest species for the rehabilitation of disturbed soils in oil fields in the Ecuadorian Amazon

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HIGHLIGHTS

- Petroleum activities may cause severe soil erosion.
- Plants of 20 species were planted in disturbed soils in oil fields in the Amazon.
- We measured plant performance and changes in soil characteristics after two years.
- Trees decrease hydrocarbons levels between 11 to 22 % in contaminated soils.
- Five species are the most suitable for restoration of oil fields in Amazon Basin.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 22 March 2016
Received in revised form 14 May 2016
Accepted 15 May 2016
Available online 27 May 2016

Editor: Jay Gan

Keywords:
Hydrocarbon contaminated soils
Forest restoration
Rehabilitation of oil fields
Sapling performance

ABSTRACT

Soils in the Amazon Basin disturbed by petroleum extraction activities need to be restored to allow for the rehabilitation of these areas and the restoration of the ecosystem services that they can provide. This study explores the performance of saplings of 20 species transplanted to four sites: a paddock and three sites within oil fields that differ in soil substrate contamination and perturbation. In each site we measured sapling survival, possible causes of death, sapling height and diameter at the time of and two years after planting, and the integrated response index. We also analyzed the effects of plants on soil properties. Sapling mortality was limited, with 17 of the 20 species boasting survival rates of over 80%. Saplings in the control site had a higher mortality rate than those in the oil field sites. This was most likely due to competition with and interference of weeds that were more abundant at the control than other sites. Despite the overall low mortality rate, species performance did vary by site, with plants of *Flemingia macrophylla*, *Myrcia* aff. *fallax*, *Piptadenia pteroclada*, *Platymiscium pinnatum*, and *Zygia longifolia* exhibiting the best performance in terms of survival and growth in oil field sites. At the end of the experiment, soil substrates from the oil platform showed increases in pH levels, organic material, Fe, and Zn; whereas substrates contaminated with petroleum showed decreases in hydrocarbon levels ranging from 11 to 22% compared to initial levels before sapling transplanting. Our results shed light on which forest

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http://dx.doi.org/10.1016/j.scitotenv.2016.05.102

species are most suitable for the rehabilitation of sites disturbed by activities inherently associated with petroleum extraction in the Ecuadorian Amazon.

1. Introduction

The degradation of soil and reduction of vegetation cover caused by human activity are increasing globally as a consequence of agriculture, grazing, mining and urban development (Bruun et al., 2015; Ferreira de Araújo et al., 2015; Ochoa et al., 2016; Russell and Ward, 2016). The loss of soil quality causes a loss in soil functional activities, and this results in the loss of the ecosystem services, resources and goods that these soils offer to humankind; these in turn have important negative effects on the geochemical, hydrological, and biological cycles of the Earth System (Berendse et al., 2015; Brevik et al., 2015; Decock et al., 2015; Smith et al., 2015; Keesstra et al., 2016).

The oil industry constitutes one of the largest and most lucrative industrial activities on the planet, as petroleum is one of humanity's main sources of energy (Pérez-Hernández et al., 2013). However, the increase in hydrocarbon extraction activities in continental regions results in the degradation and erosion of vast territories (Namkoonga et al., 2002), thereby creating one of the most severe environmental problems in the world (Übelhör et al., 2014).

Soil degradation is one of the most negative impacts of the activities inherent to petroleum extraction (Orta Martínez et al., 2007). It is caused by the removal of plant cover and upper soil layers during the construction of drilling platforms, as well as by the contamination of soils with hydrocarbons, heavy metals, and other chemical substances that are stored as byproducts in mud and drill cutting cells and contaminated soil treatment units in the oil field facility (Willis et al., 2005). Moreover, the construction of drilling platforms is done using heavy machinery, which leads to soil compaction (Startsev and McNabb, 2000) and affects soil's physical properties (Håkansson and Reeder, 1994).

In the Latin American region, countries such as Guatemala, México, Perú, Bolivia, Nicaragua, Panamá, and Ecuador are all carrying out petroleum extraction activities even in protected areas, threatening the natural heritage of the region with the highest level of biodiversity on the planet (Gentry, 1993). In Ecuador, petroleum is the main source of income, and it is essential to the country's economic development. Approximately 4.2 million ha — 15% of Ecuador's entire territory – are altered by petroleum extraction activities, and most of this area lies within Amazonian ecosystems. Consequently, oil fields require rehabilitation to reduce both on-site effects (soil erosion, loss of soil fertility, and soil contamination) and off-site effects such as sediment accumulation in rivers and reservoirs (Jorgenson and Joyce, 1994). The sediment and water leaving the oil fields contains pollutants that may reach bodies of water downstream, further affecting natural resources and, potentially, human health (Ko and Day, 2004).

Forest restoration activities are essential tools to rehabilitate degraded areas and to restore part of the form, functions and ecosystem services that these areas delivered before the human-induced land perturbation occurred (Hobbs and Harris, 2001). Restoration of the vegetation cover generally leads to improvements in soil properties (Fialho and Zinn, 2014; de Moraes Sá et al., 2015; Ochoa-Cueva et al., 2013), as has been previously demonstrated in Ecuador and other South American regions. After a few years of revegetation, organic matter increases and biological activity is stimulated (Jones et al., 2004), restoring the functions of the soil. Moreover, these enhanced soil properties and the plants growing in them can neutralize or stabilize the soil contaminants, potentially rendering them unavailable to other organisms (Merkl et al., 2004).

A successful restoration process depends largely upon the selection of plant species and the ability of these to adapt to degraded soil conditions (Bradshaw and Huttl, 2001). At a global level, some studies have been carried out to select plant species for soils disturbed by petroleum extraction activities, and to assess the effects of these species on soil characteristics in tropical and subtropical ecosystems (e.g., McConkey et al., 2012 and Willis et al., 2005 in America, and Mohsenzadeh et al., 2010; Shirdam et al., 2008 and Xia, 2004 in Asia). However, as far as we know there are no such studies in the Amazon Basin. In the Ecuadorian Amazon, the reforestation projects in oil fields have mostly selected a combination of native and exotic species based on the knowledge of farmers and local technicians, rather than on any systematic study that determined species' suitability to restore these sites. Thus, these reforestation projects were largely unsuccessful, partly due to unknown plant performance, growth, or adaptability to the specific conditions of contaminated soils, and partly due to an inadequate control of weeds. This has led to low survival levels, and very poor species growth following transplanting (Villacís et al., 2016).

The main objective of this study was to evaluate the performance of 20 tree species planted in areas disturbed by activities associated with petroleum extraction in Amazonian Ecuador. For the two years following their planting, we tested the performance of these trees on different sites: a paddock control site and three sites within the oil fields' facilities that differ in soil compaction and contamination. We also evaluated the effect of these plants on soil characteristics to assess whether the use of these species could feasibly be used as a tool to improve soil characteristics. We hypothesized that soil contamination by hydrocarbons and heavy metals in oil fields would have the worst impact on plant growth and survival irrespective of the species planted, while other soil physicochemical perturbations (soil compaction and clearance of the first soil horizon, the organic horizon) would have a lower impact on plant performance compared to plants growing in surrounding paddocks. Moreover, we expected that surviving plants would have a measurable effect on soil properties two years after planting. The ultimate goal of this study was to produce a list of species recommended for their use in restoration projects of oil fields in the Amazon Basin based on their abilities to survive, grow, and amend soils affected by petroleum extraction activities.

2. Materials and methods

2.1. Study site

The study was performed in the Sucumbíos (0° 5′S, 76° 53′W) and Orellana (0° 56′S, 75° 40′W) provinces in the Ecuadorian Amazon (Fig. 1). Both provinces have an average altitude of 328 m, a mean annual precipitation of 3000 mm, a mean annual temperature of 25 °C, and a relative humidity of 85%. The area is classified as "tropical rainforest" (Peel et al., 2007). Soils in this area are typically acidic, and have low nutrient levels and high aluminum contents (Villacís et al., 2016); these singularities lead to rapid soil erosion and infertility after the vegetation is removed from the oil fields (Nichols et al., 2001).

Taking into account the availability of sites located in the study area, as well as the site facilities provided by PETROAMAZONAS Company, we selected a number of paddocks used to cultivate pasture for livestock as control sites, and three types of sites within the petroleum extraction facilities (hereby referred to as "disturbed sites"), all of which differed in substrate compaction and contamination by hydrocarbons and heavy metals. The petroleum extraction process begins with the selection of a site, the removal of the vegetation and upper soil layer, and the creation of oil-platforms where oil drilling will occur. These drilling activities create contaminated residue material called "drilling mud" and "drill cuttings", which are solids that are found in the drilling stream. These solids are then transported to an area called "mud and drill cutting