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# SELECTION OF ADEQUATE SPECIES FOR DEGRADED AREAS BY OIL-EXPLOITATION INDUSTRY AS A KEY FACTOR FOR RECOVERY FOREST IN THE ECUADORIAN AMAZON

Jaime Villacís[1]*, Cristina Armas[2], Susana Hang[3], Fernando Casanoves[4]

[1]*Departamento Ciencias de la Vida, Universidad de las Fuerzas Armadas (ESPE), PO Box 171-5-231B, Av. General Rumiñahui s/n, Sangolquí, Ecuador*
[2]*Estación Experimental de Zonas Áridas, Consejo Superior de Investigaciones Científicas, Almería, Spain*
[3]*Facultad de Ciencias Agrícolas, Universidad Nacional de Córdoba, CC 5095000 Córdoba, Argentina*
[4]*Biometric Unit, Tropical Agricultural Research and Higher Education Center (CATIE), Turrialba, Costa Rica*

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## ABSTRACT

One of the requirements for the forest restoration of soils disturbed by the oil-exploitation industry is that saplings be able to endure soil-adverse conditions. In this study, saplings of 20 species susceptible to be used in reforestation programs were evaluated for their ability to grow on substrates derived from soils disturbed by petroleum extractions in the Ecuadorian Amazon. Seeds of each species were planted in germination trays. Once seedlings reached 5 cm in height they were transplanted to plastic bags with three treatment substrates: two derived from petroleum-exploitation activity (soils from mud and drill cutting cells and from areas surrounding oil wells) and a control soil. Plant survival rate, stem height, and diameter were measured on a weekly basis until 14 weeks after transplantation, when we harvested the plants and also measured plant biomass and calculated the Dickson quality index for each species. Oil-exploitation by-product substrates impaired the performance of many saplings, with the substrate from mud and drill cutting cells being the one that most affected plant performance. Only saplings of five native species in the Amazon basin—*Apeiba membranaceae*, *Cedrelinga cateniformis*, *Inga densiflora*, *Myroxylon balsamum*, and *Pouroma cecropiifolia*—exhibited high or similar Dickson quality index values in all soil treatments and performed better than the rest. The use of these five species in remediation of soils disturbed by petroleum extraction in the Amazon basin could prove important because of their high potential to adapt to these disturbed sites. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: forest restoration; reforestation; mud and drill cutting cells; oil platforms; Amazon basin

## INTRODUCTION

Land degradation is a worldwide problem that is triggered by human activity (Meshesha *et al*., 2012; Sarah & Zonana, 2015). Erosion, pollution, and soil degradation are environmental impacts recognized throughout the world as consequences of agriculture and industrial activities (Cerdà *et al*., 2009a; Keesstra *et al*., 2016; Novara *et al*., 2016; Prosdocimi *et al*., 2016). Land degradation affects soil quality, and its study requires an interdisciplinary approach (Brevik *et al*., 2015). The recovery of degraded soils is necessary to regain the services that the soil offers to humankind (Keesstra *et al*., 2012).

Oil or petroleum-exploitation industry is considered the main industrial activity that causes the most severe erosion of soils (Hashim *et al*., 2007). The most adverse impacts of terrestrial oil extraction industry are land disturbance and soil degradation (Orta Martínez *et al*., 2007). Inland oil-exploration industry implies the construction of routes to new oil-extraction sites, vegetation clearing and topsoil removal to build the oil platforms, and soil contamination due to waste materials. The oil well is placed in the middle of a platform, a flat area of ~2 ha where topsoil has been removed, and used to build steep slopes or it is placed in surrounding areas. These slopes and the surrounding area have no contact with hydrocarbons or other residues, and these are only compacted soil. The residues generated by the soil drilling and oil extraction are called "mud and drill cutting waste material." This waste material is placed in ponds (usually 1000 $m^3$ in volume and 4 m in depth) built in locations called "mud and drill cutting cells," big areas of different sizes where the vegetation has been cleared and that includes a variable number of ponds. The waste material is then manipulated in these ponds, and it is mixed with the topsoil that was removed during oil platform construction, with silt, clay, and many chemicals including antifoam compounds, phosphate esters, fatty acids, sodium chloride, sodium silicate, sodium carbonate, and polyoxalate alcohols in order to stabilize and accelerate the stabilization process of the material in the ponds and reduce its toxicity (Scholten *et al*., 2000; Willis *et al*., 2005).

Overall, oil extraction results in severe impacts on natural ecosystems, such as natural habitat destruction and fragmentation (Forman & Deblinger, 2000), high rates of erosion, sediment transport, and soil compaction, during the construction, oil transport, and normal activity in oil exploitations (Startsev & McNabb, 2000). This type of soil erosion not only reduces soil fertility but also changes its physical structure and biota (Carpenter *et al*., 2004), usually creating

*Correspondence to: J. Villacis, Departamento Ciencias de la Vida, Universidad de las Fuerzas Armadas (ESPE), PO Box 171-5-231B, Av. General Rumiñahui s/n, Sangolquí, Ecuador.
E-mail: jevillacis@espe.edu.ec

very unfavorable conditions for plant growth. This is of particular concern in Ecuador, as petroleum is a major source of income. Since the 1970s it has been the nation economy engine (ECB, 2013) but at the expense of expanding the area occupied by this activity within the high-biodiversity hot spot Amazon basin ecosystems. Approximately 4·2 million ha, 15% of Ecuador whole territory, is affected by petroleum activities (Guaranda, 2011), and these pursuits are in conflict with conserving the rich biodiversity in the region. In such a scenario, restoration of the vegetation cover is required and can be achieved only via reforestation programs (Vieira *et al*., 2015). In fact, soil degradation in oil-extraction sites is often considered as deleterious because the impact of mining and in both cases site remediation is required after the activity ceases (Haigh *et al*., 2015; Pallavicini *et al*., 2015).

There are several reforestation programs on oil-exploitation sites that are currently active in Ecuador (Villacís *et al*., 2014). However, some programs have been unsuccessful because of the poor survival and low growth rates of planted tree seedlings (Engel & Parrotta, 2001). There are several reasons for this failure; the most likely is the lack of understanding of soil characteristics, knowledgeable selection, and performance of species in the nursery or lack of systematic analyses of species growth patterns and performance in the field being restored (McConkey *et al*., 2012). From those few studies that have analyzed the suitability of a set of plant species, the majority analyzed only the height and diameter of planted species (Xia, 2004) and a few measured plant biomass and carbon assimilation (Willis *et al*., 2005). In this study, we screened the performance of saplings of 20 species on substrates derived from oil platforms and mud and drill cutting cells for their possible use in the restoration of degraded areas by oil-exploitation industry in the Ecuadorian Amazon.

## METHODS

### *Field Study and Species*

The study was performed in the installations of PETROAMAZONAS EP (PetroAmazonas hereafter). The study area was located in the Cantón Lago Agrio (0°5′32″, 4°54′52″ W; elevation 328 m asl), in the NW Amazon region in the Sucumbíos Province, Ecuador (Figure 1). The area is classified as a "tropical rainforest" (Peel *et al*., 2007). Annual rainfall is approximately 3000 mm, and the mean annual temperature is 25 °C. Soils are distropepts, red, acidic, clayish, and shallow and with high contents of toxic aluminum (SECS, 1986).

We selected 20 species based on unpublished data from PetroAmazonas and discussions with local technicians and farmers. Fifteen of these species are native, and five are exotic species; species that grow naturally in the Amazon basin are considered native, while those species that have been introduced from other areas are considered exotic (Gentry, 1993; Pennington *et al*., 2004). These species are commonly

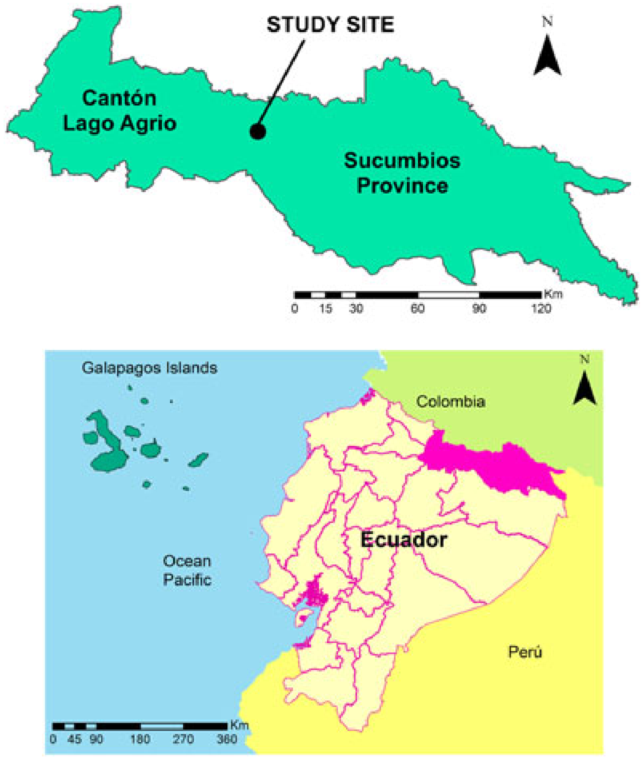


Figure 1. The study area: Cantón Lago Agrio, Sucumbios, Ecuador. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

selected, mainly because of the availability of enough seeds as well as their value for the local population (Table I). Seeds of each species were collected between November 2011 and June 2012 from randomly selected and healthy, vigorous trees in the surrounding forest to the PetroAmazonas nursery. We buried one seed per pot ($n = 100$ seeds per species). These pots were arranged in germination trays of 50 plastic inverted pyramid-shaped pots, and they were filled with a standard germination substrate (PRO-MIX PGX, Premier Tech Ltd, Quebec, Canada). Time to radicle emergence (germination), percent germination, and time until seedling reached 5 cm in height are displayed in Table II. Seeds were considered germinated when they had a radicle protruding more than 2 mm (criterion of embryo axis growth; Schopfer & Plachy, 1984).

Once the seedlings reached 5 cm in height (between 11 and 70 days), they were transplanted into 1-L plastic bags containing one of three substrates (see in the next section for how substrate treatments were created and Table III for substrate characteristics). Seedlings were first placed in 75% shade and then moved into progressively less shaded conditions every 2 weeks for their acclimation to full sun conditions. Plants were watered daily from 7:00 to 8:00 AM with a sprinkler and were left to grow for 14 weeks—this being the average time that plants spend in the nursery prior to transplantation.

### *Soil Treatments*

We collected two types of by-product substrates from the oil-exploitation site (Figure 2) and created a substrate as a control. The first "soil" (T1) is a substrate collected from

Table I. Taxonomic classification and some uses of the 20 species analyzed in this study

| Scientific name | Family | Common name | Origin | Use |
|---|---|---|---|---|
| *Acnistus arborescens* (L.) Schltdl. | Solanaceae | **Pico pico** | Native | Wood/medicinal |
| *Apeiba membranaceae* Spruce ex. Benth. | Malvaceae | **Peine de mono** | Native | Ornamental/ medicinal |
| *Averrhoa carambola* L. | Oxalidaceae | **Carambola** | Exotic | Timber-fruit |
| *Cedrela odorata* L. | Malvaceae | **Cedro** | Native | Timber |
| *Cedrelinga cateniformis* (Ducke) Ducke | Fabaceae | **Chuncho** | Native | Timber |
| *Flemingia macrophylla* (Willd.) Merrill | Fabaceae | **Flemigia** | Exotic | Fodder |
| *Inga densiflora* Benth. | Fabaceae | **Guaba** | Native | Wood/fruit |
| *Leucaena leucocephala* (Lam.) de Wit | Fabaceae | **Leucaena** | Exotic | Fodder |
| *Morinda citrifolia* L. | Rubiaceae | **Noni** | Exotic | Fruit |
| *Myrcia* aff. *fallax* | Myrtaceae | **Onte** | Native | Wood |
| *Myroxylon balsamum* (L.) Harms | Fabaceae | **Bálsamo** | Native | Timber/medicinal |
| *Ochroma pyramidale* (Cav. ex Lam.) Urb. | Malvaceae | **Balsa** | Native | Timber |
| *Piptadenia pteroclada* Benth. | Fabaceae | **Guarango espinudo** | Native | Timber |
| *Platymiscium pinnatum* (Jack.) Dougand | Fabaceae | **Caoba** | Native | Timber |
| *Pouroma cecropiifolia* Mart. | Urticaceae | **Uva de monte** | Native | Fruit/medicinal |
| *Stryphnodendron porcatum* D.A.Neill & Occhioni f. | Fabaceae | **Guarango rojo** | Native | Timber |
| *Syzygium malaccensis* (L.) Merr. & L.M.Perry | Myrtaceae | **Pomarrosa colombiana** | Exotic | Wood/fruit |
| *Tapirira guianensis* Aubl. | Anarcadiaceae | **Capulí amazónico** | Native | Timber |
| *Vitex cymosa* Bertero ex Spreng. | Verbenaceae | **Pechiche** | Native | Timber |
| *Zygia longifolia* (Humb. & Bond. ex Willd.) Britton & Rose | Fabaceae | **Chíparo** | Native | Wood/fruit |

mud and drill cutting cells, and, thus, it contains not only hydrocarbons but also different chemicals. The second “soil” (T2) was collected from the areas surroundings oil wells, and it is hereby referred to as oil-platform soil. This soil is the red subsoil typical of the Amazon basin but mixed and compacted during the construction of the oil platform and slopes. It thus has no oil contaminants. The control “soil” (control) was provided by the PetroAmazonas nursery. It is a substrate commonly used to ensure successful and healthy seedling growth during the nursery stage, and it is composed of surrounding forest topsoil and coffee subproducts in a proportion of 1:1 (v/v) and the addition of a 10–30–10 (N, P, and K) fertilizer and lime to alkalize the substrate. This soil treatment has no contaminant and was included in this study as control treatment to mimic local practices.

We made a composite of 10 collected samples per soil treatment and analyzed the following soil characteristics: soil texture, which was determined by the hydrometer method; soil electrical conductivity and pH, which were measured in each composite sample using a 1:10 (w/v) aqueous solution with a conductivity and a pH meter (Thermo Scientific, Carlsbad, CA, USA); and soil organic material (SOM),

Table II. Mean time to radicle emergence and percentage germination of seeds and time to reach 5 cm height of seedlings of the 20 species analyzed, $n = 100$

| Species | Time to radicle emerge (days) | Germination (%) | Time to reach 5 cm height (days) |
|---|---|---|---|
| *Acnistus arborescens* | 9 | 88 | 39 |
| *Apeiba membranaceae* | 10 | 72 | 83 |
| *Averrhoa carambola* | 12 | 100 | 30 |
| *Cedrela odorata* | 9 | 58 | 28 |
| *Cedrelinga cateniformis* | 6 | 82 | 11 |
| *Flemingia macrophylla* | 6 | 74 | 30 |
| *Inga densiflora* | 3 | 92 | 14 |
| *Leucaena leucocephala* | 5 | 84 | 14 |
| *Morinda citrifolia* | 24 | 98 | 70 |
| *Myrcia* aff. *fallax* | 13 | 98 | 24 |
| *Myroxylon balsamum* | 17 | 88 | 57 |
| *Ochroma pyramidale* | 6 | 48 | 14 |
| *Piptadenia pteroclada* | 3 | 54 | 21 |
| *Platymiscium pinnatum* | 5 | 94 | 14 |
| *Pouroma cecropiifolia* | 13 | 88 | 37 |
| *Stryphnodendron porcatum* | 6 | 99 | 14 |
| *Syzygium malaccensis* | 9 | 96 | 23 |
| *Tapirira guianensis* | 10 | 98 | 19 |
| *Vitex cymosa* | 11 | 40 | 38 |
| *Zygia longifolia* | 6 | 92 | 16 |

 

Table III. Physicochemical characteristics of the different substrates where plants grew

| Characteristics | Units | $T_1$ (mud and drill cutting cells soil) | $T_2$ (oil-platform soil) | Control soil |
|---|---|---|---|---|
| Texture | | Clayey | Clayey | Sandy loam |
| Organic matter (SOM) | $g\,kg^{-1}$ | 4 | 10 | 64 |
| pH | (soil : water 1:2·5) | 4·5 | 4·3 | 6·3 |
| $NH_4$ | $mg\,kg^{-1}$ | 9·9 | 20·0 | 18 |
| P | $mg\,kg^{-1}$ | 3·9 | 3·8 | 50 |
| S | $mg\,kg^{-1}$ | 29·0 | 24·0 | 6·8 |
| Zn | $mg\,kg^{-1}$ | 0·7 | 0·40 | 2·2 |
| Cu | $mg\,kg^{-1}$ | 1·4 | 3·10 | 3·9 |
| Fe | $mg\,kg^{-1}$ | 23 | 43·00 | 70 |
| Mn | $mg\,kg^{-1}$ | 6·1 | 2·50 | 4·7 |
| B | $mg\,kg^{-1}$ | 0·57 | 0·22 | 0·61 |
| Electrical conductivity | $dS\,m^{-1}$ | 0·06 | 0·04 | 0·23 |
| Al + H | meq/100 mL | 3·2 | 4·50 | - |
| Al | meq/100 mL | 1·6 | 1·44 | - |
| Ca | $C_{mol}\,kg^{-1}$ | 2·0 | 1·2 | 11·2 |
| Mg | $C_{mol}\,kg^{-1}$ | 0·27 | 0·30 | 2·3 |
| K | $C_{mol}\,kg^{-1}$ | 0·02 | 0·06 | 3·6 |
| Na | $C_{mol}\,kg^{-1}$ | 0·13 | 0·13 | 0·26 |
| Cation exchange capacity | meq/100 g | 8·4 | 8·90 | 17·3 |
| Saturation | % | 28·8 | 18·9 | 100 |
| Total petroleum hydrocarbons | $mg\,kg^{-1}$ | 1149·80 | | |
| Polycyclic aromatic hydrocarbons | $mg\,kg^{-1}$ | $<0·3$ | | |
| Cd | $mg\,kg^{-1}$ | 0·68 | | |
| Ni | $mg\,kg^{-1}$ | 8·76 | | |
| Pb | $mg\,kg^{-1}$ | 24·42 | | |

which was measured by dry combustion and, finally, cation exchange capacity by barium chloride. We also measured the following elements: $NH_4^+$ content by using the Kjeldahl distillation method and determined with a PerkinElmer Lambda 25 spectrophotometer (Waltham, MA, USA); K, Ca, Mg, Fe, Cu, Zn, Mn, and P contents by following a modified Olsen method and measured with a SavantAA Σ atomic absorption spectrophotometer (SavantAA Sigma, Hampshire, IL, USA); S and B contents by the $CaHPO_4$ method; and Al and Al + H by the NaOH titration method. These analyses were performed at Instituto Nacional de Investigaciones Agropecuarias del Ecuador. The concentrations of potential soil contaminants in mud and cutting drill cell substrate were estimated by analyzing the total petroleum hydrocarbon and polycyclic aromatic hydrocarbon concentrations with GC-2014 gas chromatograph (Shimadzu Scientific Instruments, Inc, Columbia, MD, USA): determination of total petroleum hydrocarbons followed the Texas Natural Resource Conservation Commission (TNRCC) 1005 method with flame ionization detection and determination of total polycyclic aromatic hydrocarbon followed the Environmental Protection Agency (EPA) SW-846 method. We also determined the concentration of cadmium (Cd), nickel (Ni), and lead (Pb) in soils by atomic absorption spectrometry (Shimadzu AA-6800, Scientific Instruments, Inc, Columbia, MD, USA) by following the EPA SW-846 method. Both analyses were performed at the oil laboratory of the Universidad de las Fuerzas Armadas, Ecuador.

### *Plant Variables Measured*

Survival rate, main stem height, and diameter were measured weekly for 14 weeks. Stem height was measured as extending from the sapling base to the apical meristem by using a metal ruler, and stem diameter was measured at 2 cm from the sapling base by using a digital caliper (error ±0·01 mm). At the end of the experiment, three plants were randomly selected and measured for their below-ground and above-ground dry mass, as well as their Dickson quality index (DQI). Fresh and dry masses were measured by using a precision balance (error ±0·01 g). Roots were cleaned with water to eliminate all soil particles. Fresh mass was then weighed, and the above-ground and below-ground parts were placed in separate paper bags in an oven at 70 °C for 48 h, and then we determined their dry mass. On the basis of these variables, we calculated the DQI for each species, which serves to determine the performance of a sapling's species in an integrated way (Dickson *et al*., 1960; Davis & Jacobs, 2005; Chirino *et al*., 2008):

$$\mathrm{DQI} = \frac{\text{total tissue dry weight (g)}}{\frac{\text{main stem height (cm)}}{\text{main stem diameter (mm)}} + \frac{\text{aboveg-round tissue dry weight (g)}}{\text{below-ground tissue dry weight (g)}}}$$

### *Statistical Analyses*

Plants growing in different soils were placed in the nursery in a completely randomized design with five replicates per each treatment and species (20 species × 3 soil treatments × 5 plants = 300 experimental units). The experimental unit consisted of a sapling placed into a 1-L plastic bag. Differences in main stem height and diameter, above-ground and below-ground biomass, and DQI under each soil treatment were analyzed separately for each species, by using general linear models (ANOVA). The saplings' stem

 

Figure 2. Pond where mud and drill cuttings cells waste material is treated and stored (top); oil platform (bottom). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

height and diameter at the beginning of the experiment were used as covariates. Differences among soil treatment levels were tested by using Fisher's LSD ($p < 0{\cdot}05$). Stem diameter and height were measured weekly and thus were analyzed by using repeated measures. Additionally, as there was a significant treatment–week interaction, we performed orthogonal contrasts each week on stem height and diameter. The first contrast evaluated differences between the performance of plants in the control substrate and the average performance of plants in the two oil-exploitation substrates [control vs (T1 + T2)/2]. The second contrast evaluated the differences in plant performance in the two oil-exploitation substrates (T1 vs T2). All analyses were performed by using the software package R v.3.2.3 (version 3.2.1.), interfaced by the INFOSTAT software (Di Rienzo *et al*., 2014).

## RESULTS

### *Survival, Stem Diameter, and Stem Height*

Irrespective of the soil treatment or species, all 300 saplings were alive at the end of the experiment except one individual of *Apeiba membranaceae* that died in the control soil treatment.

The mud and drill cutting cells substrate (T1) had an overall negative effect on stem diameter and plant height of the studied species. Fifteen out of 10 species showed at the end of the experiment less height and diameter growing in mud and drill cutting cells substrate than in oil platform substrate (T2) or control substrate. Plants of 9 of these former 15 species (*Acnistus arborescens*, *A. membranaceae*, *Averrhoa carambola*, *Flemingia macrophylla*, *Leucaena leucocephala*, *Morinda citrifolia*, *Ochroma pyramidale*, *Piptadenia pteroclada*, and *Zygia longifolia*; Table S1) had higher growth in control substrate than the other treatments, indicating low tolerance to both substrates from oil-exploitation sites. Nonetheless, some species grew equally well in all substrates: *Cedrelinga cateniformis* and *Syzygium malaccensis* plants exhibited similar height and diameter in all soil substrates, *Myroxylon balsamum* plants showed similar height and *Myrcia* aff. *fallax* plants showed similar diameter across soil treatments. Finally, plants of *Cedrela odorata*, *Inga densiflora*, *Platymiscium pinnatum*, and *Stryphnodendron porcatum* had similar height and diameter when growing in oil-platform (T2) and control substrates.

When analyzing main stem diameter and height increases along the 14 weeks of growth, only plants of three species displayed no significant differences in growth across soil treatments (*C. cateniformis*, *M. balsamum*, and *S. malaccensis*; Table S2), while the remaining species showed significant differences in main stem height and diameter growth after 1 week of growth in the different soil substrates. Results from the first contrast [control vs (T1 + T2)/2] indicate that plants of *A. arborescens*, *F. macrophylla*, *O. pyramidale*, *P. pteroclada*, and *Pouroma cecropiifolia* displayed significant differences at 4–6 weeks after transplantation (Figure 3), suggesting that both stem diameter and plant height were negatively affected by by-products from oil-exploitation sites. Results from the second contrast (T1 vs T2) indicate that there were no differences in stem diameter or plant height between saplings growing on either substrate of by-products from oil-exploitation sites along the whole experiment (there was not a significant treatment × time interaction) for the following six species: *F. macrophylla*, *L. leucocephala*, *P. cecropiifolia*, *S. malaccensis*, *Tapirira guianensis*, and *Z. longifolia*. *M.* aff. *fallax* and *S. porcatum* saplings displayed a significant treatment × time interaction beginning in week 4, and other species presented significant interactions for only one variable: *I. densiflora* differed only in main stem diameter starting at week 11, and *A. carambola* significantly differed between weeks 5 and 9 (Table S2).

### *Above-ground and Below-ground Biomass*

The results indicate some significant differences in above-ground and below-ground biomass among soil treatments. Fourteen out of 20 species had more above-ground and below-ground biomasses (and thus total biomass) when growing in control substrate than in any substrate of by-products from oil-extraction activities (Table S3). These differences in biomass were important as saplings of 8 of

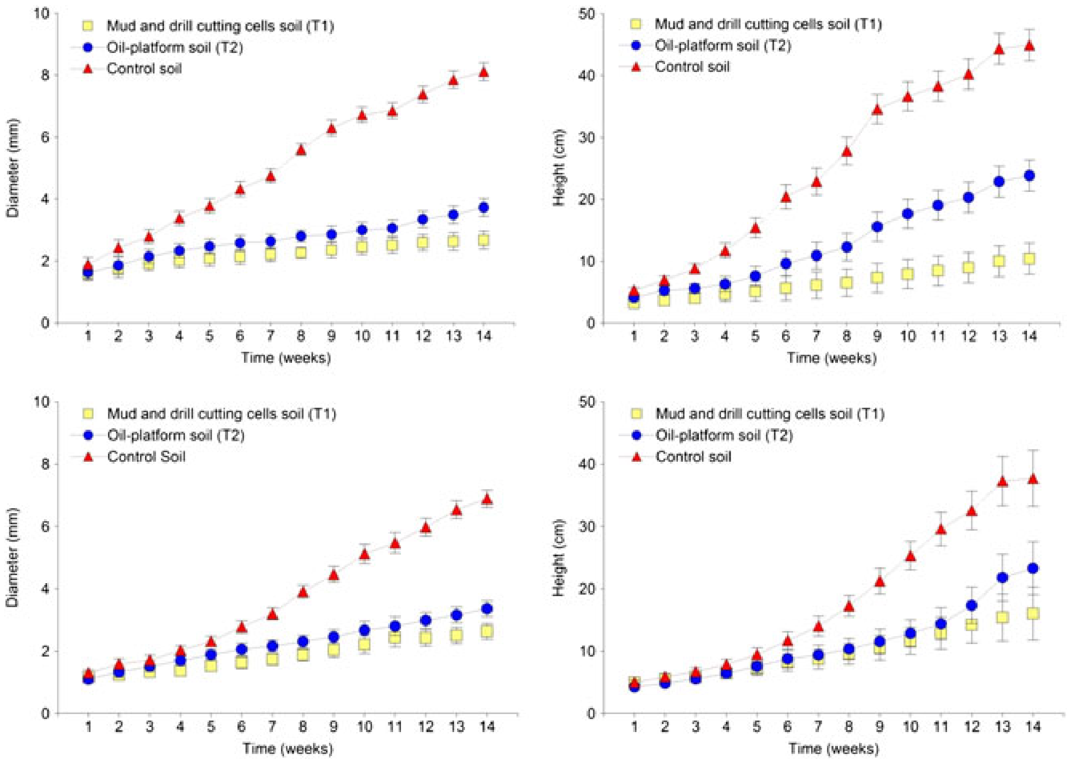


Figure 3. Main stem diameter (left) and height (right) of plants of two species that displayed differences in growth in control and oil-exploitation substrates during a period of 14 weeks: *Ochroma pyramidale* (top) and *Acnistus arborescens* (bottom). Data are mean values +/− SE (n = 5). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

these 14 species had two times the total biomass, and saplings of the other 6 species had three times the total biomass of saplings growing on oil-extraction by-product substrates compared with those grown in control substrate (Figure 4). Only *A. membranaceae* and *M. balsamum* saplings grew equally well in all soils and irrespective of the plant biomass part analyzed. These two former species, *F. macrophylla* and *Vitex cymosa*, had similar total biomass across treatments. *I. densiflora* and *V. cymosa* showed similar aboveground mass, and *S. malaccensis* and *P. cecropiifolia* had similar root mass across soil substrates.

### *Quality Index*

Accordingly, DQI results were higher in control soil treatment than oil-extraction by-product substrates for 14 of the 20 species analyzed (Table IV). Only saplings of five species, *A. membranaceae*, *C. cateniformis*, *I. densiflora*, *M. balsamum*, and *P. cecropiifolia*, displayed similar DQI values across soil treatments, while *S. porcatum* saplings exhibited similar DQI values under T2 and control soil treatments.

## DISCUSSION

Our multiple-species evaluation may be an essential initial step in selecting viable and successful plant species for the reforestation of degraded areas by oil-extraction industry in Amazon basin. The vast majority of saplings survived after 14 weeks of growing in any of our treatment substrates. However, compared with control soils, substrates of oil-exploitation sites impaired the performance of many saplings, with the substrate from mud and drill cutting cells being the one that most affected plant performance. Nonetheless, plants of five native species in Amazon basin (*A. membranaceae*, *C. cateniformis*, *I. densiflora*, *M. balsamum*, and *P. cecropiifolia*) grew equally well in all treatment substrates, and, thus, they may be the most suitable species to be included in reforestation programs on petroleum-exploitation disturbed soils in the Ecuadorian Amazon.

### *Performance of Species on Substrates*

All saplings but one survived irrespective of the soil treatment applied. However, in many reforestation programs, transplanting shock can be a real problem and a cause of high mortality across species (Ashton *et al.*, 1995). Thus, this is one of the key variables considered in the selection of appropriate species for reforestation (Elliott *et al*., 2003; Davis & Jacobs, 2005), although our results show that saplings transplantation did not have any significant impact on sapling survival.

During the first 3 weeks after transplantation, saplings of the same species had similar height and stem diameter irrespective of the soil substrate where they grew, probably because their roots were still covered by PRO-MIX PGX germination substrate, and, thus, initial growth might have not been affected by soil treatments. After this initial period, sapling growth was greatly influenced by substrate quality. Plant growth of 17 out of 20 species was impaired

 

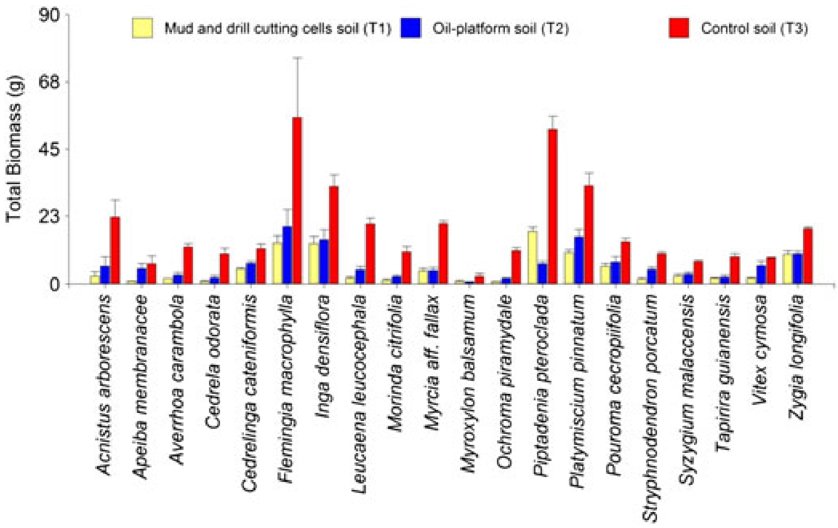


Figure 4. Total biomass at the end of the experiment (14 weeks after seedling transplant) of seedlings of 20 species growing in different soil treatment levels: soil from the mud and drill cutting cells (T1), from the oil platform (T2), and control soil. Bars within a species with different letters are significantly different (LSD Fisher *post hoc* test, $p < 0.05$). Data are mean values +/− SE (n = 5). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

when growing in the substrate treatments from oil-exploitation sites; plants had either lower height and/or stem diameter at some point along the experiment, and at the end of the experiment, 15 of these 17 growth-impaired species were smaller when growing in mud and drill cutting cell substrate compared with when they were grown in the control substrate. Similar results were reported by Willis *et al*. (2005) and Xia (2004), who suggested that soil disturbance has an impact on the growth of various plant species in soils of oil platforms in subtropical coastal regions. Additionally, Merkl *et al*. (2005) and Shirdam *et al*. (2008) found a delay in the growth and performance of plants that grew on petroleum-contaminated soils in tropical coastal areas.

In our study, the substrate from mud and drill cutting cells had also significant concentrations of hydrocarbons, Cd, Ni, and Pb that might have negatively affected plant growth. Although the concentration of these contaminants in the mud and drill cutting cells substrate is considered permissible for these fragile ecosystems (MAE, 2001), that does not mean that they did not affect plant performance. Even if the levels of these compounds in the soil were not high

Table IV. Dickson quality index at the end of the experiment (14 weeks after seedling transplant) of saplings of 20 species growing in different soil treatment levels: soil from the mud and drill cutting cells (T1), from the oil-platform (T2), and control soil. Data are mean values +/− SE (n = 5). Values within a species with different letters are significantly different (LSD Fisher post hoc test, p<0·05)

| | DQI | | | |
|---|---|---|---|---|
| Species | T1 | T2 | Control soil | *p*-value |
| *Acnistus arborescens* | 0·43 ± 0·18 b | 0·90 ± 0·50 b | 3·96 ± 1·34 a | 0·0478 |
| *Apeiba membranaceae* | 0·15 ± 0·01 a | 0·72 ± 0·29 a | 0·81 ± 0·27 a | 0·1700 |
| *Averrhoa carambola* | 0·36 ± 0·02 b | 0·52 ± 0·15 b | 1·62 ± 0·09 a | 0·0012 |
| *Cedrela odorata* | 0·06 ± 0·02 b | 0·15 ± 0·05 b | 0·62 ± 0·13 a | 0·0051 |
| *Cedrelinga cateniformis* | 0·65 ± 0·06 a | 0·86 ± 0·10 a | 1·22 ± 0·18 a | 0·0510 |
| *Flemingia macrophylla* | 1·80 ± 0·27 b | 2·25 ± 0·57 b | 7·90 ± 2·43 a | 0·0442 |
| *Inga densiflora* | 0·98 ± 0·16 a | 1·19 ± 0·39 a | 2·04 ± 0·11 a | 0·0514 |
| *Leucaena leucocephala* | 0·23 ± 0·07 b | 0·47 ± 0·12 b | 1·50 ± 0·11 a | 0·0003 |
| *Morinda citrifolia* | 0·19 ± 0·06 b | 0·40 ± 0·09 b | 1·61 ± 0·25 a | 0·0013 |
| *Myrcia* aff. *fallax* | 0·57 ± 0·16 b | 0·43 ± 0·08 b | 2·31 ± 0·47 a | 0·0067 |
| *Myroxylon balsamum* | 0·12 ± 0·07 a | 0·08 ± 0·02 a | 0·26 ± 0·10 a | 0·2738 |
| *Ochroma pyramidale* | 0·14 ± 0·003 b | 0·24 ± 0·04 b | 1·26 ± 0·12 a | 0·0001 |
| *Piptadenia pteroclada* | 1·74 ± 0·27 b | 0·74 ± 0·12 b | 5·50 ± 0·92 a | 0·0021 |
| *Platymiscium pinnatum* | 1·32 ± 0·23 b | 1·95 ± 0·25 b | 3·91 ± 0·68 a | 0·0141 |
| *Pouroma cecropiifolia* | 1·25 ± 0·26 a | 1·24 ± 0·19 a | 1·97 ± 0·21 a | 0·0938 |
| *Stryphnodendron porcatum* | 0·15 ± 0·05 b | 0·45 ± 0·08 a | 0·67 ± 0·03 a | 0·0023 |
| *Syzygium malaccensis* | 0·41 ± 0·10 b | 0·51 ± 0·10 b | 1·15 ± 0·09 a | 0·0031 |
| *Tapirira guianensis* | 0·25 ± 0·04 b | 0·25 ± 0·07 b | 0·98 ± 0·17 a | 0·0048 |
| *Vitex cymosa* | 0·21 ± 0·03 b | 0·49 ± 0·16 b | 0·82 ± 0·05 a | 0·0120 |
| *Zygia longifolia* | 1·39 ± 0·24 b | 1·20 ± 0·11 b | 2·74 ± 0·16 a | 0·0016 |

Values are mean ± 1 SE, $n = 3$; *p*-values are those resulting from an analysis of variance for each species separately and with soil treatment as the fixed factor. Values within a species with different letters are significantly different (LSD Fisher *post hoc* test, $p < 0.05$).

 

enough to be lethally toxic, they might have impaired nutrient uptake by plants, as these chemicals can create a hydrophobic layer around the roots impairing nutrient uptake (Gill & Tuteja, 2010). It is worth noting that substrates from mud and drill cutting cells are waste material that has been thoroughly mixed with the parent soil together with many chemicals to stabilize and reduce waste material toxicity (see introduction). Substrate composition is then expected to be homogeneous in the 4-m-deep mud and drill cutting ponds, and when reforestation will occur, all plant species to be transplanted into these ponds will have permanent contact with soil contaminants irrespective of each species' root system.

Most importantly, plant biomass was strongly affected by substrate quality. The total biomass of 16 of the 20 species growing in substrates of oil-exploitation sites was at least half of that of plants growing in the control substrate, probably due to the poor physicochemical characteristics of these substrates (low levels of P, Zn, Ca, Mg, and K; medium to high levels of Cu, Fe, Mn, and B; and high Al levels), as well as the presence of hydrocarbons, which limits the absorption of nutrients in soils (Ferraz, 1993). In this sense, Brandt *et al*. (2006) and Rutherford *et al*. (2005) found a reduction of 36–56% of total biomass in plants growing on oil-contaminated soils.

### *Implication for Management*

The use of the most suitable tree species in reforestation programs in degraded areas not only increases the probability of successful plant establishment; it is also known to usually increase soil organic matter content, trigger secondary succession (Zahawi, 2005), and reduce soil erosion at different scales (Keesstra, 2007). Additionally, vegetation cover protects soil from the direct impact of wind and water (Li *et al*., 2007), thereby mitigating soil erosion and surface runoff (Cerdà *et al*., 2009b) as compared with exposed soil (Ochoa *et al*., 2016), as well as reducing the amount of sediment discharged into rivers (Keesstra *et al*., 2009). Ultimately, the successful establishment of a necessary vegetative cover on degraded areas depends on the proper selection of tree species (Roman-Dañobeytia *et al*., 2012).

Despite the great differences found in the morphological variables between treatments, five native species displayed similar DQI values among treatments: *A. membranaceae*, *C. cateniformis*, *I. densiflora*, *M. balsamum*, and *P. cecropiifolia*. Moreover *C. cateniformis*, *I. densiflora*, and *P. cecropiifolia* also had high biomass irrespective of the substrate. This supports results from previous field trials and provides persuasive evidence that the ability of plants to grow on oil-disturbed soils varies among species (Wiltse *et al*., 1998; Liste & Alexander, 1999). Therefore, tree species that have the capacity to grow well in oil-contaminated soils should be used in remediation programs, not only to restore vegetation cover but also to degrade and transform contaminating residue into less toxic compounds (Pilon-Smits, 2005). These five optimal species are all native and have ecological and economic values that make them adequate candidates for their use in soil remediation and reforestation programs in oil-exploitation sites in the Amazon basin. *C. cateniformis, I. densiflora*, and *M. balsamum* are legumes that do not require nutrient-rich soils and are ideal to remediate oil-contaminated soils (Bento *et al*., 2012), and *A. membranaceae* and *P. cecropiifolia* tolerate low-fertility soils and are multipurpose species (CATIE, 2000).

On the other hand, 14 of the 20 species showed lower DQI quality on oil-industry by-product substrates compared with control soils, and, thus, they would be the last ones that should be selected for reforestation programs here. Nonetheless, it is important stressing again that, irrespective of the species, all plants but one survived. Thus, despite the fact that the growth of these species may be negatively affected when growing in disturbed oil-industry soils, they can still be used in reforestation programs and managers should evaluate the pros and cons of increasing species richness and potential ecological benefits of planting multiple species in these reforestations. It should be noted that five of our studied species are legumes (*F. macrophylla*, *L. leucocephala*, *P. pteroclada, P. pinnatum*, and *Z. longifolia*) and they were the species that showed the largest biomass. They can therefore play an important role in reforestation programs, as they can accelerate soil remediation, diversify the plantations, and generate higher ecological benefits (Harvey *et al*., 2005). However, because these degraded soils are deficient in nutrients, amendments and organic fertilization may be necessary to further improve the performance of these species.

## CONCLUSION

Plant response to substrates of oil platforms areas and mud and drill cutting cells was species specific. The stem diameter and height of saplings of 15 species and the total biomass of saplings of 16 species were impaired when growing on substrates of oil platforms and mud and drill cutting cells as compared with when they were grown on the control substrate. Only saplings of five native species in the Amazon basin—*A. membranaceae*, *C. cateniformis*, *I. densiflora*, *M. balsamum*, and *P. cecropiifolia*—exhibited high or similar performance across all soil treatments and performed better than the other 15 species. The high tolerance to substrates derived from oil-disturbed soils of these five forest species could render these species as the most successful and suitable to be used in future restoration programs of oil-exploitation sites in the Amazon basin. The results of this study may be useful in the planning of restoration programs in areas disturbed by oil extractions in the entire tropical rainforest areas of the Amazon basin, as the same oil extraction process is conducted throughout the region using the very same technology.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site:

**S1.** Main stem height and main stem diameter at the end of the experiment of seedlings of 20 species growing in different soil treatment levels.

**S2.** Number of weeks when height and diameter of seedling were significantly different between the control soil and the average of the two red soils and between the two red soils.

**S3.** Above– and below–ground biomass at the end of the experiment of seedlings of 20 species growing in different soil treatment levels.