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Modeling bio-engineering traits of *Jatropha curcas* L.

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ABSTRACT

The wide distribution of *Jatropha curcas* L. in tropical areas provides the opportunity to use this plant for improving slope stability and controlling erosion. To determine the effectiveness of *Jatropha curcas* L. as a bio-engineering plant we measured stem diameter and height of 1, 3, 5, 6, 18, and 36 month-old plants, and root distribution at 6, 18, and 36 months by full excavation of the root system. We also measured in the laboratory the elastic modulus and maximum tensile force of 50 roots. These data were used to calibrate a weighted log-likelihood root distribution model and a root reinforcement model. Models were coupled to estimate root reinforcement at stand scale over a three year period as a function of the plantation's tree density. Our results of root distribution indicate a rapid decrease of root diameter along the root length leading to rapidly decreasing root reinforcement with distance from the stem. Minimal root reinforcements at 0.5 m from the stem is about 1 and 11 kPa for 18 and 36-month old plants, respectively. At 1 m from the stem only 36-month old plants provide any significant root reinforcement.

Despite its relatively low root reinforcement relative to other larger tree species *Jatropha curcas* L. is a suitable bio-engineering plant because it easily propagates, grows fast, and is resilient. Root reinforcement in the first stage of growth needs high density plantation of up to 40,000 plants per hectare. This should then be followed by thinning down to 10,000 plants per hectare to optimize root reinforcement at 3 years age.

1. Introduction

Control of erosion and soil instabilities is a challenge in many areas of the world. Mitigation of these effects using man-made steel or concrete structures is often costly and long-term economic sustainability should favor bio-engineered remedies that support local populations when possible. Research on plants and their bio-mechanical and biological properties has shown that plant roots can improve soil geotechnical and hydrological properties: roots improve soil stability through a combination of factors such as root–soil friction, root tensile strength, production of root exudates, microbial activity, and soil cover (Stokes et al., 2014; Graf and Frei, 2013; Wani et al., 2012). Hence studying bio-engineering traits (Stokes et al., 2009) such as root strength, root spatial distribution, and root growth over time is necessary to quantify the efficiency of a plant to improve erosion control and slope stability. Bio- (or eco-) engineering is based on the study of the physical interactions between soils and plants with the objective of understanding the mechanical and hydrological behaviour of rooted-soils.

Jatropha curcas L. is a perennial plant native of central America growing spontaneously in tropical monsoon climates such as in tropical Africa and south Asia (Maes et al., 2009) (Am and Aw zones, following the Köppen–Geiger climate classification (Peel et al., 2007)). It has been planted extensively as a crop for biodiesel production (Contran et al., 2013). Its potential as a plant for bio-engineering applications is recognised by many because of its high above- and below-ground biomass, resilience (the capacity to regenerate itself after cutting), growth in poor soils, soil and water conservation, and erosion control effectiveness (Heller, 1996; Openshaw, 2000; Dagar et al., 2006; Chikara and Jaworsky, 2007; Petrone and Preti, 2008; Reubens et al., 2011; Kagamèbga et al., 2011; Wani et al., 2012; Ghestem et al., 2014a,b; Ehrensperger et al., 2015).

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Table 1
Soil characteristics, mean and standard deviation on four samples.

Soil content	Values	Units
Sand	62.1 ± 3	%
Clay	19.5 ± 2	%
Silt	18.5 ± 2	%
Bulk density	1.46	$g\,cm^{-3}$
pH	8.3 ± 0.1	–
Carbon total	13 ± 0.8	$g\,kg^{-1}$
Organic matter	22.25 ± 1.26	$g\,kg^{-1}$
Nitrogen total	1.25 ± 0.06	$g\,kg^{-1}$
C/N	10.5 ± 0.5	–
Phosphorus (P_2O_5)	59.5 ± 11.1	$mg\,kg^{-1}$
Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+})	10.3 ± 0.7	$meq\,hg^{-1}$

From a mechanical point of view, Ghestem et al. (2014b) made the first attempt to estimate root reinforcement of soils with *Jatropha curcas* L. roots carrying out direct shear tests on rooted soils using 10-month old plants. They found a significant increase in yield stress for the rooted soils. Quantification of root reinforcement, however, is a challenge because of the large variability of root strength (Loades et al., 2010) and root distribution. No study has yet modelled the root distribution of *Jatropha curcas* L. or provide a complete data set that permitted the calculation of root reinforcement in terms of the dynamic strain–stress behaviour of the roots.

Here we further explore the effects of *Jatropha curcas* L. roots on soil strength using the Root Bundle Model (RBM) of Schwarz et al. (2013). We make estimates of root reinforcement at the stand scale using laboratory data of root strength and measurements of root density on an experimental plantation in Sardegna, Italy. The RBM is based on the fiber bundle model (Cohen et al., 2009) and improves significantly estimates of root reinforcement made using classical models. An important difference with classical theories (e.g., Wu et al., 1979) is that not all roots break at the same time and maximum root reinforcement is not additive to the soil cohesion because it occurs at a different displacement from the maximum soil shear strength (Cohen et al., 2011; Giadrossich et al., 2013). Furthermore, the RBM of Schwarz et al. (2013) introduces a convenient model for root strength variability in different root diameter classes by introducing a Weibull survival function.

The aims of this paper are: (i) model the horizontal root distribution of *Jatropha curcas* L. root system for 6, 18 and 36-month old plants; (ii) apply the RBM of Schwarz et al. (2013) on a hypothetical stand to assess the effects of the bio-engineering root reinforcement over a three year time period; (iii) provide growth curves for *Jatropha curcas* L.

2. Materials and methods

2.1. *Jatropha curcas L. plantation*

Seeds of the Indian variety of *Jatropha curcas* L. collected in Ghana (Yendi road Farm, Northern Region) were planted in a greenhouse in the experimental farm of Ottava, Sardinia, Italy (40°46′31.12″ N 8°29′12.62″ E). Seeds were sowed in April 2012 in polystyrene alveolar tray cells filled with fully irrigated potting mix medium (dry matter 30% of volume, organic matter 20% of volume, Fertilizer N:P:K = 12:14:24). Fourty eight seedlings of *Jatropha curcas* L. were transplanted in May 2012 to a 6 by 16.5 m plot, and spaced 1.5 m apart, 12 plants in a row. The soil was classified as a sandy loam. Soil thickness in the greenhouse varied from 35 to 55 cm with a regular gradient along the longest side of the plantation. Soil properties are given in Table 1. Because the plants were also part of a project on photosynthesis, the 48 plants were grouped in two water-supply rates: 2.45 and 4.9 l per week (about 130 and 260 mm per year). In November 2013 plants were separated hydraulically from one another by a plastic liner positioned vertically over the whole depth of the soil profile. The root distribution analysis was performed on the same number of plants for each water-supply rate. Bio-mechanical measurements were carried out (see next paragraph) with no evidence of any difference between the two water-supply rates. Data were thus combined into a unique dataset.

2.2. *Field and laboratory measurements*

We took biometric data (height and stem diameter) of plants 1, 3, 5, 6, 18, 36-month old. Twenty-four root systems were measured to obtain the root distribution. Root distributions of 8 6-month old plants were measured by means of the strait trench wall method (Silva and Rego, 2003; Krishnamurthy et al., 2012) at 0.3 and 0.6 m from the plant stem. The 6-month old data were interpreted as being nearly equal to a root distribution found at 0.25 and 0.5 m distance from the tree stem. Then, to obtain more precise data on root distribution, the entire root systems of 8 other plants was dug up carefully in November 2013 (18-month old plants) and 8 more in April 2015 (36-month old plants) with an excavator. Root distribution of 18 and 36-month old plants was measured by image analysis (Bischetti et al., 2009; Hales et al., 2009). For each plant, the stump with its roots was placed on a 10-cm gridded tarp avoiding excessive twisting or strechting of the root system. High-resolution images were obtained with a digital camera positioned above the stem axis. The number of roots per 1 mm root diameter class was counted using a computer-aided-design software (Bischetti et al., 2009) at four distances from the stem: 0.10, 0.25, 0.50, and 1.0 m. The maximum rooting distance from the stem was also measured.

Tensile force tests were carried out on 50 samples (segments) of 6-month old *Jatropha curcas* L. roots in the laboratory using a universal testing machine (LF-Plus Chatillon) no later than one week after sampling (Bischetti et al., 2009). Root samples were 40 mm long, with a minimum, maximum, and median diameter of 0.4 mm, 3.6 mm, and 1.5 mm, respectively.

2.3. *Root distribution model*

We used the root distribution model of Schwarz et al. (2012) to predict the distribution of roots at different growing stages of the plant. The model assumes a uniform azimuthal distribution of roots around the stem (Reubens et al., 2011). Because of its focus on lateral root reinforcement, the model does not examine root distribution with depth. The following set of equations allows estimation of the number of roots for one plant for each root diameter class i at a given distance, d, from the stem. The maximal rooting distance from the stem is given by

$$d_{\max} = \psi\phi_s, \tag{1}$$

where ψ is a scaling factor and ϕ_s is the diameter of the tree at breast height (for *Jatropha curcas* L. the diameter at collar was used). The density of fine roots (less than 2 mm) crossing a 1-m wide vertical section of soil, ρ_{fr}, is given by

$$\rho_{fr}(d) = \left(\frac{\mu\left(\phi_s^2\frac{\pi}{4}\right)}{d_{\max}2\pi d}\right)\left(\frac{d_{\max}-d}{d_{\max}}\right), \quad d < d_{\max}, \tag{2}$$

where μ is a pipe coefficient (number of roots per square meter). The density of coarse roots, ρ_{cr}, is

$$\rho_{cr}(d_s,\phi_i) = \rho_{fr}\left(\frac{\ln(1+\phi_{\max})-\ln(1+\phi_i)}{\ln(1+\phi_{\max})}\right)\left(\frac{\phi_i}{\phi_0}\right)^{\gamma}, \tag{3}$$

where γ is a constant exponent, ϕ_i is the root diameter class size i (in millimetres), ϕ_0 is a reference diameter (1 mm), and ϕ_{max} is the