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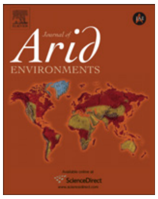

Short Communication

More than biofuel? *Jatropha curcas* root system symmetry and potential for soil erosion control

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ABSTRACT

One of the reasons why *Jatropha curcas* has recently been hailed as one of the world's most sustainable biofuel crops, is its suitability to grow on arid land where it offers the additional benefit of erosion control. As arid lands are often very vulnerable to land use changes, it is nevertheless important to fully understand (belowground) plant functional and structural development before they are planted at large scale. Here we introduce possible measurement methods for the root system structure of *J. curcas* seedlings and adult plants, formulate a set of hypotheses on root system structure, and demonstrate these in the light of root structure stability. Initially developing one taproot and four perpendicularly oriented laterals, the root structure of *Jatropha* appears to be quite promising to control soil erosion by water and wind on arid land. The lateral roots could decrease soil erodibility through additional soil cohesion, while the taproot and sinkers may enable exploitation of subsurface soil moisture and thus enhance vegetative cover, even in very dry environments.

1. Introduction

As an oil-bearing small perennial, claimed to be adapted to tropical semiarid regions and marginal sites (Maes et al., 2009a), *Jatropha curcas* L. currently receives great attention as a sustainable solution for simultaneous fuel production, socio-economic development, and wasteland reclamation in degraded areas (Achten et al., 2010a).

Regarding the latter, a strong soil erosion control potential is attributed to *Jatropha* (Behera et al., 2010). However, scientific proof of this statement is yet to emerge (Achten et al., 2008). Profound knowledge of the structure and functioning of *Jatropha* roots under different growth conditions is necessary to understand this potential role. Such information will also increase insight in *Jatropha*'s ecological functioning or potential protection functions (Achten et al., 2007). Although never formally investigated, several reports, including Heller (1996) and Severino et al. (2007), mention a consistent and symmetrical initial rooting system (one taproot and four perpendicular laterals) for *Jatropha* plants during germination and seedling stage. At least two conditions need to be fulfilled for such root architecture to develop and to be preserved: (i) seed propagation (cuttings do not develop a taproot) and (ii) free growth in suitable soil conditions (Heller, 1996; Severino et al., 2007). This study focuses on individuals propagated from seeds. Our aim is to:

1. Provide a quantitative description of the root structure of *Jatropha* from an explorative sample of seedlings and adult trees;
2. Formulate hypotheses related to *Jatropha* root structural development, focussing on symmetry and consistency;
3. Highlight key aspects to be considered when appraising the species' erosion control potential;
4. Provide methodological recommendations for measuring *Jatropha* root structure.

2. Materials and methods

2.1. Initial root system structural development

Root structural development of *Jatropha* seedlings was studied within a larger greenhouse experiment in Leuven (Belgium), dealing with *Jatropha* biomass production, allometry, plant–water

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relationships and growth strategies (Achten et al., 2010b; Maes et al., 2009b). Seedlings were grown in plant containers (Ø 41 cm – height 28 cm) from *Jatropha* seeds (Arba Minch, Ethiopian accession) directly sown in the centre of the containers after nicking and cold water treatment (see also Maes et al., 2009b).

In August 2007, four 2-week-old and seven 4-week-old seedlings were harvested and evaluated. Root architectural measurements were performed by dividing the root systems into axes (individual roots) and root segments. Segments end at a branching point or at sudden change of root diameter or growth direction. At the base of every root axis and the end of each root segment (Ø ≥ 0.5 mm) the diameter and XYZ coordinates were recorded, the latter using a frame consisting of moveable rulers (Danjon and Reubens, 2008). Remarks such as growth along the container wall or root breakage were recorded for detailed data interpretation. Fresh and dry mass (oven-dried at 70 °C until constant weight) were recorded for above and belowground plant material.

The root system structure was represented as a multi-scale tree graph (MTG), and analyzed in AMAPmod (plant architecture modeling and analysis software, Godin et al., 1997) and R statistical package (R Core Development Team, 2002) following Danjon et al. (2005). The stump is defined as the top portion of the first order root on which the bigger initial lateral roots branch. The remainder of the first order root is called taproot (Danjon and Reubens, 2008; Reubens et al., 2009). Higher order roots are referred to as laterals (i.e. first order *laterals* are second order *roots*).

Based on literature and personal observations (Fig. 1), a theoretical model root system for *Jatropha* seedlings was developed, characterized by a vertically oriented first order root and four main second order roots. These second order roots (i) are perfectly symmetrically distributed in the horizontal plane, (ii) have the same diameter distribution, (iii) have an oblique inclination ≈ −45°, and (iv) show a simultaneous generation at the same depth along the first order root (≈ 2.5 cm).

Based on this model root system, symmetry-related plant traits were defined, calculated for each of the measured seedlings, and rescaled to a 0–1 scale:

1. Symmetrical distribution of the four main second order roots in the horizontal plane:

$$\beta_{symm} = ((\beta_{12} - 90) + (\beta_{23} - 180) + (\beta_{34} - 270))/540 \quad (1)$$

with β_{ij} the horizontal angle between two neighbouring main roots *i* and *j*, root numbers increasing with increasing azimuth value.

After rescaling: 0 = perfectly symmetrical, 1 = all laterals coinciding.

2. Symmetrical diameter distribution of the four main roots:

$$D_{symm} = \mathrm{Max}D_{lat}^2 / \sum D_{lat}^2 \quad (2)$$

with D_{lat} the diameter at the onset of a main lateral root.

After rescaling: 0 = perfectly equal allocation, 1 = everything allocated to one root.

3. Deviation from the oblique (−45°) downward inclination:

$$\theta_{symm} = \left(\sum \mathrm{Abs}(\theta_1 - (45))\right) \Big/ 4 \quad (3)$$

with θ_i the inclination angle of root *i*. After rescaling: 0 = perfectly oblique roots, 1 = all roots are horizontal or vertical.

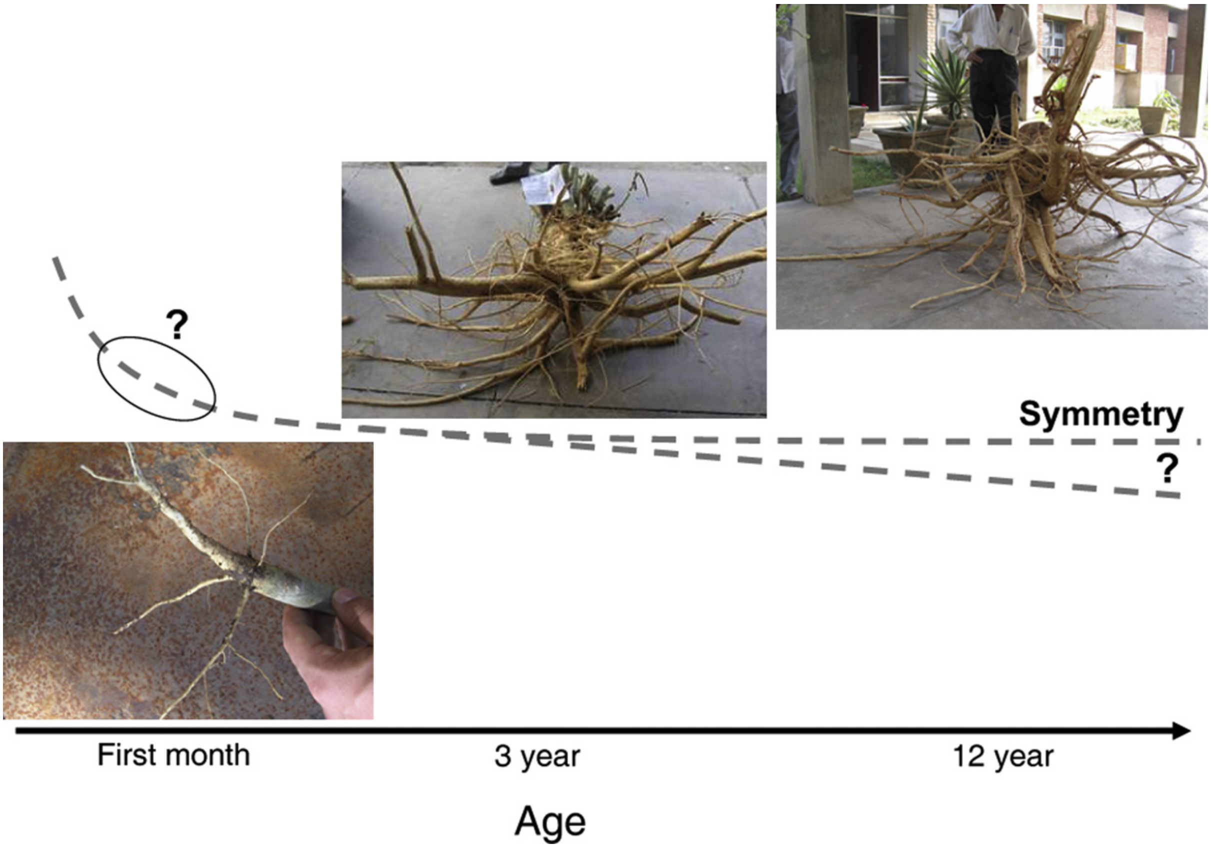

Fig. 1. Trends in root system structural development: a decreasing then stabilising symmetry with increasing size? Left: two-week-old seedling; centre and right: 3- and 12-year-old tree, respectively, showing the trunk on top, a dense network of branching laterals, and a strongly tapered taproot down.

Two variables are derived from the "root crown" or LCM, which is defined as the **L**ength on the first order root between the root base (**C**ollar) and the branching point of the four **M**ain roots:

4. Mean deviation from the standard LCM (2.5 cm):

$$\Delta_{\text{LCM}} = \text{Abs}(\text{Mean}_{\text{LCM}} - 2.5)/(\text{Max}((\text{stump Length} - 2.5), 2.5)) \tag{4}$$

with Mean_{LCM} the mean length between the collar and the branching point.

After rescaling: 0 = Mean_{LCM} is 2.5 cm, 1 = all main roots are branching from the bottom of the stump or immediately at the collar.

5. Variability within the LCM values for the individual laterals:

$$\begin{aligned}\text{LCM}_{\text{symm}} = {} & ((\text{LCM}_2 - \text{LCM}_1) + (\text{LCM}_3 - \text{LCM}_2) \\ & + (\text{LCM}_4 - \text{LCM}_3))/\text{Stump Length}\end{aligned} \tag{5}$$

with LCM_i being LCM for root i, and root numbers with increasing LCM values.

After rescaling: 0 = all main laterals originate at the same point, 1 = two roots originate at the collar and two at the bottom of the stump.

Deviations from the proposed model plant were assessed for all seedlings, by plotting the score of each indicator on a pentagonal diagram, with the five indicators forming the axes. The smaller the area occupied by the diagram, the higher the similarity. Furthermore a global score of similarity to the model (SI) was defined as:

$$\begin{aligned}\text{SI} = {} & (\beta_{\text{symm}} + D_{\text{symm}} + \theta_{\text{symm}} + 0.5 \times \Delta_{\text{symm}} \\ & + 0.5 \times \text{LCM}_{\text{symm}})/4\end{aligned} \tag{6}$$

This SI is zero for root systems perfectly matching the model.

2.2. *Root system structure of adult Jatropha trees*

Three 3-year-old trees, growing in a 2 × 4 m^2 plantation, and three 12-year-old trees growing in a 4 × 4 m^2 plantation, were uprooted in September 2008 by means of tractor power after loosening the loamy sand soil. These *Jatropha* plants were grown in the fields of Haryana Agricultural University, Bawal, India (annual rainfall: 300–550 mm, no additional irrigation). All plants were transplanted as bare-rooted saplings propagated from seeds in nursery beds.

The diameter was measured at the root collar, at the first order root immediately above and below the main second order roots, and at several additional points along the taproot. For each measurement point along the first order root, depth from the soil surface was recorded. For the main second order roots, depth of origin, initial axis diameter, total length (up to the breaking point), inclination, initial azimuth or orientation, fresh and dry mass (oven-dried at 70 °C until constant weight) were determined. Weight was also determined separately for the first order root, the four main second order roots, aboveground branches and leaves.

3. Results and discussion

3.1. *Initial root system structural development*

Both two-week-old and four-week-old seedlings revealed a uniform structure, with four dominant second order roots (Fig. 1,

Table 1

Summary of relevant root characteristics (mean ± s.d.) for *Jatropha curcas* seedlings and adults.

Variable (unit)	Seedlings		Variable (unit)	Adult plants	
	Two weeks ($n = 4$)	One month ($n = 7$)		3 year old ($n = 3$)	12 year old ($n = 3$)
Structural characteristics					
$\text{Diameter}_{\text{root base}}$ (mm)	6.32 ± 0.35	12.70 ± 2.91	$\text{Diameter}_{\text{root base}}$ (mm)	182.50 ± 27.07	233.96 ± 31.79
$\text{Diameter}_{\text{meanlat}}$ (mm)	1.27 ± 0.16	3.28 ± 0.17	$\text{Diameter}_{\text{meanlat}}$ (mm)	60.40 ± 9.75	70.67 ± 22.30
Total root volume (cm^3)	1.46 ± 0.11	8.55 ± 5.73			
$\text{Relative volume}_{\text{tap}}$ (%)	19.46 ± 9.17	50.21 ± 19.57			
$\text{Relative volume}_{\text{4lat}}$ (%)	81.0 ± 0.9	45.0 ± 1.9			
Total root length (cm)	89.35 ± 10.24	216.70 ± 93.42			
$\text{Relative length}_{\text{OI}}$ (%)	11.0 ± 0.2	14.2 ± 1.2	$\text{Length}_{\text{OI}}$ (cm) [a]	117.50 ± 16.26	169.50 ± 20.51
$\text{Relative length}_{\text{4lat}}$ (%)	79.0 ± 0.4	54.0 ± 1.8	$\text{Length}_{\text{meanlat}}$ (cm)[a]	106.13 ± 0.53	140.25 ± 23.50
N^0 of 1st order laterals (−)	4.0 ± 0.0	7.5 ± 3.2	N^0 of 1st order laterals[b]	11.50 ± 2.12	−
Root structure similarity					
LCM (cm)	2.48 ± 0.25	2.65 ± 1.42	LCM (cm)	27.67 ± 12.70	26.67 ± 2.52
Mean inclination main laterals (°)	−50.7 ± 7.9	−45.1 ± 14.3	θ_{meanlat} (°)	−36.63 ± 19.83	−21.37 ± 9.25
β (°)	90.13 ± 0.43	90.04 ± 0.94	β (°)	90.00 ± 16.73	89.69 ± 22.19
β_{symm} (−)	0.036 ± 0.020	0.082 ± 0.041	β_{symm}	0.08 ± 0.00	0.15 ± 0.06
D_{symm} (−)	0.069 ± 0.029	0.207 ± 0.201	D_{symm}	0.22 ± 0.12	0.19 ± 0.01
θ_{symm} (°)	0.172 ± 0.071	0.252 ± 0.139			
Δ_{LCM} (−)	0.069 ± 0.061	0.261 ± 0.195			
LCM_{symm} (−)	0.000 ± 0.000	0.064 ± 0.102			
Similarity Index	0.078 ± 0.024	0.176 ± 0.108			

OI: 1st order root, i.e. taproot + stump; tap: taproot; meanlat, 4lat: referring to an average for one or to the total of four main laterals, respectively.

Relative Volume or Length: volume or length of a specific root compartment as proportion of the total root system. Relative volumes are exclusive of the stump, which actually occupies most (>60%) of the total root volume.

β: mean azimuth angle between two neighbouring main lateral roots.

β_{symm}: azimuth symmetry measure main laterals (0 = perfectly symmetrical, 1 = all laterals coinciding (same azimuth)).

D_{symm}: Diameter symmetry measure main laterals (0 = perfectly equal allocation, 1 = everything allocated to one root.).

θ: inclination angle between the root origin and the point where the root reaches the deep root zone.

θ_{symm}: measure for the deviation from the oblique (45°) inclination (0 = perfectly oblique roots, 1 = all roots are horizontal or vertical).

LCM: length from base to the 4 laterals.

Δ_{LCM}: mean deviation from the standard LCM (2.5 cm) (0 = Mean_{LCM} is 2.5 cm, 1 = all main roots are branching from the bottom of the stump or immediately at the collar).

LCM_{symm}: variability within the LCM values for the individual laterals (0 = all main laterals originate at the same point, 1 = two root originate at the collar and two at the bottom of the stump).

[a] values up to root breaking point, i.e. an underestimate of the actual value.

[b] for adult trees if D_{base} >25 mm.

left). These four main roots originated at about the same depth (LCM ≈ 2.48–2.65 cm) along the first order root, and had an average inclination of −45 to −50° (Table 1). Deviation from the model was low for the youngest seedlings (8% on average). This symmetrical development was reflected in all symmetry indicators. After four weeks, deviation from the model had increased (18%), although symmetry was still strong (see Fig. 2, and β_{symm}; D_{symm} and LCM_{symm} in Table 1).

For the two-week-old seedlings, the four dominant second order roots were the only higher order roots, representing 79% of the total root length (81% of the total root volume) (Table 1). After one month an average of 7.5 ± 3.2 second order roots and a small amount of third order roots had developed. Along with increasing age and development of additional roots, the relative importance of the four main roots decreased (54% of the total length and 45% of the total volume after four weeks). An opposite trend was observed for relative taproot length (11–14%) and volume (19–50%) (Table 1).

3.2. Root system structure of adults

Except for one 12-year-old individual, all examined trees had four clearly dominant second order roots, with an inclination angle between −20 and −40° (oblique) (averages in Table 1), and branching from the first order root at a depth of about 25 cm. This is relatively deep compared to what was observed for the seedlings, and might be due to initial planting depth or sediment deposition. The low β_{symm} values indicate a symmetrical horizontal distribution of the onset of each of these main roots. Although not perfectly symmetrical, their diameters are similar, as reflected by the relatively low D_{symm} (0.19–0.22) (Table 1).

Root system observation in the field and photographic interpretation (Fig. 1, centre and right) revealed that the initial 4 second order roots remained dominant in adult *Jatropha* trees. However, these adult individuals did not maintain their initial ‘typical’ rooting structure, but developed a more branched root system. Generally this rooting system consisted of three main types of big structural roots: (i) four to eight far-reaching, quasi horizontal laterals, (ii) a set of oblique or almost vertically growing laterals (sometimes including sinker roots, parallel with the first order root), (iii) the taproot itself, limited in vertical extension, but splitting into several structural roots which continue to grow with a strong inclination.

A clear stump was observed till the depth where the main roots originated. Below that point the first order root tapered very rapidly. At the branching point a set of smaller second order roots originated as well. In the topsoil, a dense net of finer horizontal laterals with many branches arose.

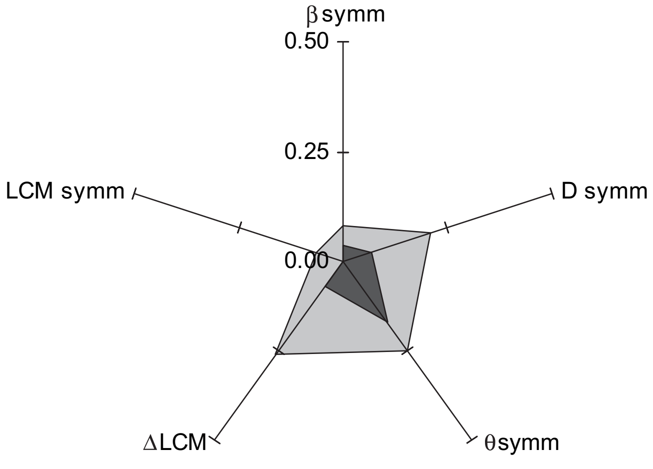

Fig. 2. *Jatropha* seedling root development: pentagonal diagram representing similarity to the model plant. *Grey*: average for two-week-old seedlings, *Black*: average for one-month-old seedlings.

3.3. Proposition of a preliminary root system type for Jatropha

Based on the aforementioned observations, the following preliminary assumptions could be formulated:

- *Jatropha* has four clearly dominant second order roots, with an initial diameter of 20–35% of the collar diameter;
- Between their branching point and their end point, these roots first develop horizontally before plunging into deeper soil;
- These roots originate symmetrically, both with regard to spatial orientation and biomass allocation;
- Over time the importance of the taproot decreases, but several new oblique and sinker roots arise, acting as anchoring stakes.

The high degree of symmetry in biomass distribution and orientation for young *Jatropha* seedlings, though uniformly true for the initial onset on the main second order roots, does not guarantee a continued symmetrical development further away from the central root stump (Foidl et al., 1996). Whereas spatially explicit vegetation models, individual plant growth models or slope stability models generally assume symmetrical radial distribution of roots (Biondini, 2001; Collet et al., 2006; Danjon et al., 2008; Dupuy et al., 2005a,b), the actual spread of lateral roots is generally quite asymmetrical due to variable soil conditions and plant-interaction (Coutts et al., 1999; Ganatsas and Spanos, 2005; Schenk et al., 1999). Given the striking symmetry for *Jatropha* at the initial growth stage, an interesting question may be if the probable decrease in symmetry with age/size follows a well-determined and species-specific pattern or not. As represented in Fig. 1 and based on the symmetry indicators assessed for young seedlings as well as 3- and 12-year-old trees (Table 1), our theory is that the symmetrical development around the root collar is reduced within a short period of time (less than one month). Nevertheless, this symmetry subsequently gradually stabilises, still remaining remarkably high (see β_{symm}; D_{symm} in Table 1). This presumption introduces several questions: How does the symmetry evolve? Is there a turning point after which a stable symmetry is reached, or does it continue to decrease? And what is the impact of root system symmetry on its structural functioning, for instance in the framework of soil erosion control?

3.4. Potential for erosion control and soil exploitation

Although *Jatropha* is regularly and pertinently claimed to have a high potential for controlling soil erosion by wind and water, the mechanisms of wind breakage and sediment capture during surface runoff generally referred to are more linked with its planting method (dense hedge planting along the slope contours), fast aboveground development and fine root density in the topsoil than with the coarse root system structure. However, the three-dimensional structure of this coarse root system as presented here may also play an important role, not only for superficial water erosion but also for slope stabilisation and control of incisive erosion processes such as rill and gully erosion. Promising traits observed for the root system structure (Fig. 1) are the presence of a number of vertically developing, deep anchoring roots, a set of shallow spreading horizontal structural roots, many finer roots, and a high degree of symmetry (De Baets et al., 2009; Reubens, 2010; Reubens et al., 2007).

Although the benefits of root symmetry will depend upon the specific function and growth conditions considered (e.g. on a steep slope or under wind loading, an asymmetrical development is more beneficial to resist these directional forces; Coutts et al., 1999; Stokes et al., 2009), the importance of an evenly spread and undisturbed root system for the juvenile anchorage is well known (Lindström and Rune, 1999). Moreover, the observed structural development of *Jatropha*'s root system also seems to offer an optimal basis for the exploitation of deeper soil horizons, an important property to access water in (semi)arid environments.

4. Conclusions

Consisting of one taproot and four perpendicularly oriented laterals, the initial development of the *Jatropha* root system is remarkably symmetrical and predictable. The lateral roots have the potential to decrease soil erodibility through additional soil cohesion, whereas the taproot and sinkers may increase resistance against shallow landsliding, enable exploitation of subsurface soil moisture and thus enhance vegetative cover, even in very dry environments.

The presented methodology, differentiated for seedlings and adult trees, is an efficient and relatively low-cost technique to perform basic structural measurements. We especially propose to further refine the presented model root system and indicators, also for adult individuals. More detailed structural, hydrological and mechanical characterisation of the rooting system (including effects of nursery treatment and plantation management) would increase the insight in *Jatropha*'s plant performance and functionality, and contribute to optimization of agroforestry and plantation systems.

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