Fruits, 2015, vol. 70(3), p. 143-151
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DOI: 10.1051/fruits/2015010

FRUITS
Available online at:
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ORIGINAL ARTICLE

Estimating root length density of pineapple (*Ananas comosus* (L.) Merr.) from root counts on soil profiles in Martinique (French West Indies)

Jean-Louis Chopart[1], Lila Debaut-Henoque[2], Paul-Alex Marie-Alphonsine[2], Rémy Asensio[2] and Alain Soler[2,⋆]

[1] Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Dept PERSYST, UPR AIDA, Station de Roujol - 97170 Petit-Bourg (Guadeloupe), French West Indies
[2] Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Dept PERSYST, UR: Banana, Plantain and Pineapple cropping systems, CAEC, BP 214, 97285 Le Lamentin cedex 2, (Martinique), French West Indies

Received 15 October 2014 – Accepted 30 December 2014

Abstract – Introduction. New ecological agricultural practices contribute to improved pest management and root development of pineapple, but tools to quantify the root development in cultural profiles in situ are lacking. The spatial distribution of the root length density (RLD) is a key factor for the absorption of water and nutrients. A robust model was sought to predict the RLD from the number of intersections of roots per unit area (RID) in a soil profile (trench method). **Materials and methods.** The procedure was based on the extraction of cubes of 1 dm^3 of undisturbed soil on profiles under pineapple plants in triplicate, in which the RID was counted on three perpendicular faces of the cubes and the RLD was measured inside the cubes. **Results and discussion.** A model predicting the RLD (*RLDc*) from counting of the RID was developed and successfully tested: $RLDc = RID.CO.CE$, where $CO = 2.65$ is an orientation coefficient, and $CE = 1.69$ is an empirical coefficient. These two coefficients are fixed. **Conclusion**. The model allows an estimate of pineapple RLD and its spatial variability from simple counts of roots on a soil profile. A practical example of this model is given, characterizing and comparing *in situ* root profiles of pineapple plants.

Keywords: French West Indies / pineapple / *Ananas comosus* / rhizosphere / root system / root length density

Résumé – Estimation de la densité de longueur racinaire chez l'ananas (*Ananas comosus* (L.) Merr.) à partir des comptages racinaires sur profils de sol en Martinique (France). Introduction. De nouvelles pratiques agricoles écologiques contribuent à améliorer la gestion des ravageurs et le développement des racines de l'ananas, mais des outils pour quantifier in situ le développement racinaire dans les profils culturaux font défaut. La répartition spatiale dans le sol de la densité de longueur racinaire (RLD), est un facteur-clé pour l'absorption d'eau et d'éléments nutritifs. Un modèle robuste a été recherché pour prédire la RLD à partir du nombre d'intersections de racines par unité de surface (RID) sur un profil de sol (*Trench method*). **Matériel et méthodes.** La procédure était basée sur l'extraction de cubes de 1 dm^3 de sol non perturbé sur des profils sous les plants d'ananas en triplicats sur lesquels ont été faits le comptage de RID sur trois faces perpendiculaires des cubes et la mesure de RLD à l'intérieur des cubes. **Résultats et discussion.** Un modèle prédisant la RLD des racines (*RLDc*) à partir des comptages de RID a été développé et testé : $RLDc = RID.CO.CE$ où $CO = 2,65$ est un coefficient d'orientation et $CE = 1,69$ est un coefficient empirique. Ces deux coefficients sont fixes. **Conclusion.** Avec ce modèle il est possible d'estimer la RLD de l'ananas et sa variabilité spatiale à partir de simples comptages de racines sur un profil de sol. Un exemple d'utilisation de ce modèle est présenté, il permet de caractériser et comparer *in situ* des profils racinaires d'ananas.

Mots clés : Antilles françaises / ananas / *Ananas comosus* / rhizospère / système racinaire / densité racinaire

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⋆ Corresponding author: `alain.soler@cirad.fr`

1 Introduction

Pineapple (*Ananas comosus* (L.) Merr) is widely produced in a variety of habitats from sub-tropical to tropical areas. Commercial production is mainly based on intensive monoculture cropping systems. According to the new European regulations, the infestation of pineapple by the soil-borne parasites *Rotylenchulus reniformis* and symphyla can no longer be controlled by pesticides in the French West Indies. These parasites reduce the efficiency of water and mineral uptake by the plant as well as weakening its anchoring in the soil. New cropping systems based on more ecological farming practices [1] aim to improve pest management and root development, but no tools are available to monitor and quantify the impact of new cultural practices on the parasites and on root development.

The spatial distribution of root length density (RLD) in the soil plays a key role in water and nutrient uptake [2]. RLD is also a good indicator of the impact of new cultural practices on root development in the soil.

Characterizing the features of the pineapple root system, especially the spatial distribution of the RLD, is thus essential. However, assessing the spatial distribution of RLD in the field is not easy because of the difficulty involved in extracting a large enough representative part of the root system due to variable root distribution, soil properties and the fragile pineapple roots. Several RLD measurement methods have already been described [3], but their implementation in the field is often costly and the data they produce are not necessarily representative of the real variability of root distribution. Mapping root intersections in a soil profile using the trench-profile method [4], which gives the root intersection density (RID), has the advantage of being possible in the field and facilitates the study of root distribution in the soil [2,5]; however, it provides no direct information on RLD. Direct empirical relationships between RID and RLD have been tested in wheat [6] and maize [7], but the robustness of the relationships obtained with this approach was often poor. A mathematical relationship between the intersection density on one side of a cube of soil and the RLD inside the same cube was formulated and found to depend on the degree of root anisotropy and orientation [8, 9]. This relationship was used and adapted for maize in the field, and led to the development of a model to describe RLD for maize from root counts in trench profiles in the field [7]. Other models describing RLD from root counts in trench profiles have also been developed for sorghum [10], upland rice [11] and sugar cane [12].

This kind of model has never been developed for pineapple, and to date, studies of the pineapple root system have been limited to non-quantitative observations on cultural profiles or on plants that had been removed from the soil. The aim of the present work was to highlight the preferential orientations of pineapple roots and to develop a robust and cost-effective method for estimating RLD from root intersection counts on soil profiles. These results should be helpful for future studies of relationships between pineapple root growth, the cropping system and soil-borne parasitism.

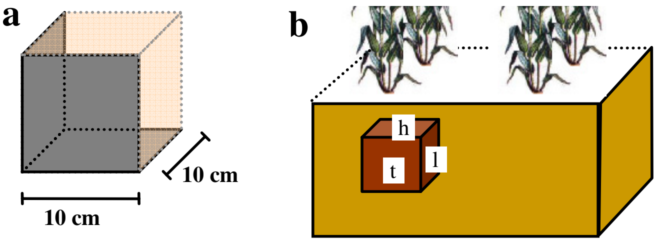

Figure 1. Root intersection density sampling and measurement procedure. a: a three-sided (0.01 m^2) partial steel cube sampling device, b: a sampling device in the soil profile, with sides oriented according to the soil surface and plant row (h: horizontal, l: longitudinal, t: transversal).

2 Materials and methods

2.1 Analysis of pineapple root anisotropy and root orientation as a preliminary study to model root length density (RLD)

The first approach used to estimate this relationship was to establish simple empirical regressions between RID and RLD. For maize [7, 12] and other crops it was found to be better to take the main root orientations into account in the model, so this second approach was also used. The theoretical aspects of the relationship between RID and RLD were analyzed by van Noordwijk [9], taking the root orientation relative to the counting plane into account. Measuring the root intersections on three perpendicular sides of a soil cube oriented according to the soil surface and plant row (*figure 1*): horizontal (h), transversal (t) and longitudinal (l) enables determination of the root anisotropy factor (AN) [8, 9] through the following relationship:

$$AN = \sqrt{\frac{((RIDh - RIDm)^2 + (RIDt - RIDm)^2 + (RIDl - RIDm)^2)}{(6.RIDm^2)}} \tag{1}$$

where RIDm is the mean RID of the three sides. AN, dimensionless, ranges from 0 (isotropy) to 1 (parallel roots). If all the roots were completely perpendicular to the counting plane, each root intersection would correspond to a root length equal to the cube side.

Pineapple (cultivar MD2, 4 months old) was grown in an experimental field in northern Martinique (French West Indies, Lat 14°4′ N, Long. 61°0′ W) on a young volcanic allophanic soil (andosol). Average annual rainfall under the wet tropical climate ranges from 2,000 to 3,000 mm, and the rain falls mainly from June to November. The crop was managed according to the locally recommended cropping method with tillage, chemical fertilization and pineapples planted in double rows on ridges (*figure 2*). The mean daily temperatures were never lower than 23 °C.

In order to analyze root anisotropy and orientation, root measurements were obtained in triplicate at 4 months after planting (MAP). In each sample, roots were sampled from

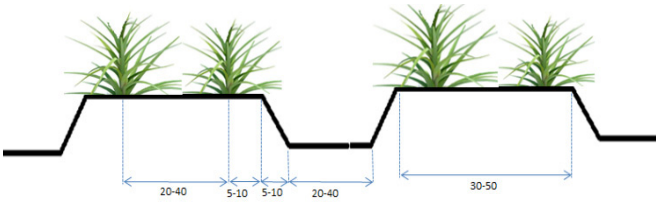

Figure 2. Distances (in cm) between pineapple rows and position of the pineapple plants on the ridges.

trench profiles dug in three different ridges. The standard RID and RLD sampling procedure was based on the extraction of 1-dm^3 cubes of undisturbed soil from open profiles using a three-sided steel cube with 10-cm long edges that were sharpened to facilitate soil penetration (*figure 1*).

This sampling device was pressed down through the soil profile until its back edge was level with the soil surface. It was then pulled back out of the soil and excess soil from the three open sides of the device was shaved off to obtain a soil cube. A second sample was taken at the same depth but the open sides of the sampling device were oriented in the opposite direction from that in the first sample so as to obtain – with the two soil cube samples – six open sides of the cube for the root counts.

Immediately after sampling, the sides of the soil cube were sprayed with water to make the root intersections easier to see and the intersecting roots visible on the three open sides of the soil cubes were counted. The number of root intersections (*NI*) enables us to calculate the root intersection densities (*RID*) for the three open sides: horizontal (*h*), transversal (*t*) and longitudinal (*l*) of each soil cube (*figure 1*), resulting in three RIDs, which were expressed in relation to the surface area of the side of the cube. The soil cubes were then brought to the laboratory and under running tap water, the roots were separated from the soil on a 1-mm-mesh sieve.

As is true for many crops, pineapple root diameters vary considerably. To determine the main root directions, it is important to distinguish between fine roots (diameter $d < 0.7$ mm) and thick roots ($d > 0.7$ mm) because they may grow in different directions. This simple distribution into two categories facilitates field observations. It was assumed that thick roots were shoot-borne and that fine roots were lateral branching roots. Preliminary studies based on full root systems have shown that this is actually the case. Hereafter, we refer to thick, fine or all roots using t, f or a indices, respectively. Next, for each sample, we determined the lengths of the fine roots and the thick roots using the line intersect method [13,14] to obtain the root length density (RLD). A total of 18 samples (1 dm^3 of soil each) were extracted from the soil.

2.2 Modeling RLD from RID

To develop the RLD model, we first selected the best method to correlate root intersection densities (RID) and root length densities (RLD), and then validated the prediction of RLD on the basis of root intersection counts (NI) in a soil plane.

RLD was modeled only on the basis of measurements of root intersections on a vertical plane because this method is the most commonly used in studies of roots on soil profiles. The reference plane (v) was therefore systematically the vertical-transversal plane. According to Lang [8] and Van Noordwijk [9], RLD can be calculated (*RLDc*) on the basis of RID measured in a vertical soil plane (v), by taking the root distribution (anisotropy and preferentially orientation) into account. A vertical coefficient (Pv) is calculated for this plane, with h representing the horizontal plane.

$$Pv = RIDh/RIDv \tag{2}$$

If $Pv > 1$ or < 1, the roots have a preferential, respectively parallel or perpendicular orientation relative to the vertical measurement plane v. For $Pv = 1$, $RLDc = 2RIDv$ [8]. These equations are used hereafter to calculate $RLDc$ values from Pv and $RIDv$. They can be combined in a general equation with an orientation coefficient (CO) representing the different aggregated factors for Pv in Equation (2):

$$RLDc = RIDv \times COv \tag{3}$$

Additional samples needed to validate the preliminary RLD model were collected at two industrial pineapple farms: (i) Gradis farm (elevation 300 m asl.), and (ii) Leyritz farm (elevation 200 m asl.), both using MD2 cultivars grown on the andosol that is typical of Martinique. The cropping systems were similar to the one used in the first experiment. Root samples were sampled below the ridge from trench profiles 4 months after planting (MAP) at Gradis, and 9 MAP at Leyritz, using the same method (double soil cubes) as that used in the first experiment. The soil cubes removed between the surface and a depth of 30 cm came from 9 samples at Leyritz and 7 samples at Gradis. The soil cubes removed between 30- and 60-cm deep came from six samples at Leyritz. Finally, 22 sets of field data were available for model validation.

Relationships between *RLD* values measured in the soil cubes (*RLDm*) and estimated by the models (*RLDc*) were tested taking into account the slope, standard error of the slope (*SE*), intercept and regression (R^2). Differences between RLDm and RLDc were also analyzed by the following statistical quantities: the Nash efficiency coefficient (*NE*) [20], root mean square error (*RMSE*) [21]) and mean bias (*MB*). *NE*, *RMSE* and *MB* should be as close as possible to 1.0% and 0%, respectively.

2.3 From RID on a trench profile to RLD mapping using the pineapple model

To estimate RLD from the number of root intersections (*NI*), the RLD model was used in the same field on Leyritz farm as the field used for model validation (§ 2.2). Three soil profiles (width 90 cm and depth 60 cm) were opened in three different ridges perpendicular to the rows of pineapple. Root counts (*NI*) were carried out on each profile using a 5-cm-mesh grid to identify the spatial coordinates of the measurements (root mapping) [15, 16]. The *NI* data were entered in Racine2 software [17] and used to calculate the RLD per unit cell of 25-cm^2 area with the RLD model.

The cell-by-cell spatialized values of RLD made it possible to estimate the percentage volume of soil potentially able

Table I. Root length density of fine (diameter < 0.7 mm) and thick (diameter > 0.7 mm) roots from the surface to a depth of 30 cm.

Age (months)	Location		Root length density (m dm^{-3})		
			Thick	Fine	All
4	Gradis	Mean	0.75	21.8	22.5
		SD	0.8	13	14
4	Mer de Chine	Mean	0.52	3.3	3.8
		SD	0.2	2.6	2.8
12	Leyritz	Mean	1.75	19.7	21.4
		SD	0.8	7.6	8.2

to ensure a sufficient supply of water or minerals to the plant, taking possible competition between the roots into account. Another model makes it possible to estimate the potential root extraction ratio (*PRER*), which depends on the distance between the roots calculated from the RLD and the estimate of the maximum migration distances of water or minerals from the soil toward the root [18, 19]. The maximum distance selected, editable in the software, was 2 cm.

3 Results and discussion

3.1 Root length densities of fine and thick roots of MD2

The root length densities between the surface and a depth of 30 cm differed considerably among the three sites (*table I*). At all three sites, the RLD were mainly due to the fine roots (Ø < 0.7 mm). From a depth of 30 cm to 60 cm, no roots were found in some cubes. The root system of pineapple had a high RLD. Between the surface and a depth of 30 cm, the average *RLD* was 21.4 m dm^{-3} (*table I*) and was sometimes more than 40 m dm^{-3} of soil near the soil surface (*figure 9*). For the purpose of comparison, sugar cane [12,13] and sorghum [10] have a maximum root length density of 20,000 and 26,000 m m^{-3} of soil, respectively. Pineapple roots are mainly located in the top 30-cm layer of the soil in the ridges with, in our conditions, a root front located about 60 cm from the plant. Sugarcane and sorghum have a much deeper root system which, in sugarcane, can penetrate to a depth of 4 m [22]. The root system of upland rice is characterized by a higher root length density (50 m dm^{-3}) in the top soil layer, at least in the case of high-yield varieties grown under favorable conditions [11]. Although upland rice and pineapple are two very different species, they both have high *RLD* near the surface characterized by a large amount of fine roots and a shallow root system.

3.2 Root anisotropy and orientation in the 0-30-cm soil layer

Root anisotropy and orientation were characterized by the *AN* and *P* coefficients (Equations 1 and 2) measuring root intersections on the three perpendicular sides of the soil cubes. Anisotropy levels were low.

Table II. Root anisotropy and orientation in the data set used for model development. An: anisotropy index, P: orientation coefficient for the vertical faces of the cube, CO: global orientation coefficient.

	Number of samples		An	P	CO
Thick roots	8	Mean	0.35	1.50	2.73
		SD	0.23	0.55	0.79
		Max	0.72	2.30	3.80
Fine roots	9	Mean	0.25	1.41	2.60
		SD	0.24	0.73	1.07
		Max	0.79	3.00	5.00
All roots	9	Mean	0.18	1.44	2.65
		SD	0.14	0.61	0.87
		Max	0.51	2.50	4.20

Based on the data set for all the roots (fine and thick), the mean anisotropy coefficient (*AN*) was less than 0.35, suggesting that root distribution was close to isotropy (*table II*). The average difference in the orientation coefficient for the vertical faces *t* and *l* ($Pt = 1.095$, $Pl = 1.085$) was very low, so the data from the two vertical faces were merged to calculate only one coefficient for the vertical faces (*Pv*) and to model the RLD. The mean value of the P orientation coefficients was less than 1.45 for the fine roots and for all the roots, and 1.5 for the thick roots, indicating a slight preferential vertical orientation of the roots ($P > 1$).

The *COv* coefficient value calculated from Equations 2 and 3 [8, 9] was 2.65 for all the roots and 2.73 for the thick roots. So, the root system geometry was close to isotropy ($CO = 2$ for isotropy) but had a slight vertical orientation. This *COv* coefficient was used to develop a geometric model to correlate root intersection on a vertical plane (*RIDv*) and RLD, taking root geometry into account.

3.3 Prediction of root length density from root counts on a trench profile: model formulation and calibration

3.3.1 All roots

Geometric model 1 (theoretical): a theoretical geometric model 1 was used to predict the measured RLD (*RLDm*), by calculating a *RLDc* from *NI* and *CO* coefficients:

$$RLDc = RIDv \times COv \tag{4}$$

where RIDv is given by the merged *NI* counts on the vertical faces (longitudinal and transversal) expressed as a function of the unit of area. The calculated all root length density (*RLDc*) obtained through (Eq. 4) led to a substantial bias (*figure 3* and Eq. 5).

$$RLDm = 1.691 \times RLDc \quad n = 9 \quad R^2 = 0.796 \quad P < 0.001 \tag{5}$$

Geometric model 2: in the geometric model 2, the discrepancy between the measured and calculated RLD with the model 1 is described by an empirical term, *CE*. The value of *CE* is the

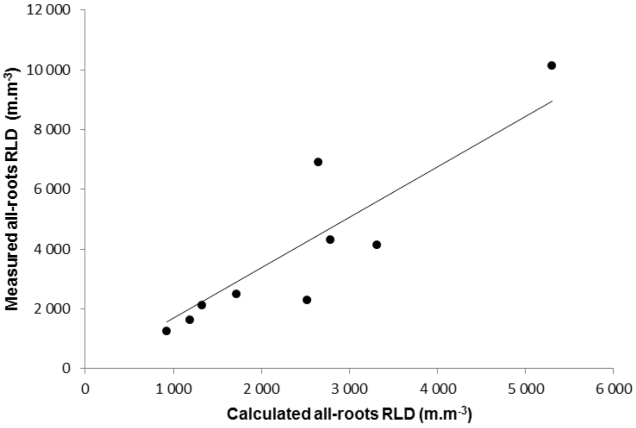

Figure 3. Calibration of the all root model. Relationship between measured root length densities (*RLDm*) and the *RLDc* calculated from $RLDc = RID \times CO$ ($CO = 2.65$).

mean value of $RLDm/RLDc$ (RLD calculated for the geometric model 1) and the *CE* value is also the slope in *figure 3* and the coefficient in Equation 5 ($CE = 1.691$). Model 2 to calculate RLD was structured as follows:

$$RLD = RID \times CO \times CE \tag{6}$$

with *CO* and *CE* according to *table II* (2.65) and Equation 5 (1.69). The empirical term *CE* has a constant value which is not related either to the *RID* or to depth (Eq. 5). A constant *CE* coefficient ($CE = 1.45$) has also been determined in upland rice [11]. For fine roots of sugarcane, the *CE* was found to be proportional to *RID* [12]. Values were from 1 to 2, close to those for pineapple. The most probable origin of the gap between *RLDc* (Eq. 4) and *RLDm* is that a significant proportion of fine roots were not counted due to the difficulties involved in counting them in the field [23]. Conventional methods of washing the soil samples can also lead to the loss of a significant proportion of roots [24]. In developing the model in the present study, great care was taken with root length measurements in order to obtain a data set of measured root lengths as close as possible to the actual value.

Empirical model: because of the low anisotropy of pineapple roots (*table II*), another simpler approach could be used, ignoring variations in root orientation and establishing a direct relation between the root intersection density counted on the vertical sides of the cube and the root length density measured inside the cube. For the all root data set (*a*), the linear regression between *RIDv* (from *NI* counts) and *RLDa* (*figure 4*) was:

$$RLDa = 4.481 \times RIDv \quad n = 9 \quad R^2 = 0.796 \quad P < 0.001 \tag{7}$$

This relation was acceptable taking the methods of measurement and the variability of field data into account. Both approaches, empirical ($RLD = 4.48 \times RID$) and geometric ($RLD = 2.65 \times 1.69 \times RID$), led to very similar calculated values due to the low anisotropy of pineapple roots. Data for the fine roots, which account for the majority of the root lengths in our samples, also showed low anisotropy, and were very close to the all root data.

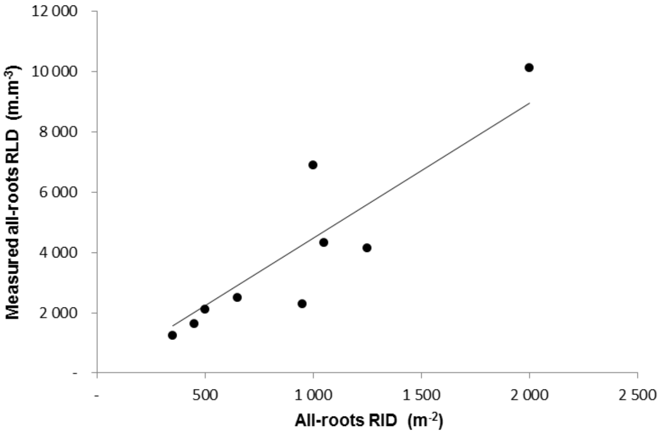

Figure 4. All root model. Relationship between the observed number of intersections per m^2 (*RID*) and measured root length density (*RLDm* in m m^{-3}) in the corresponding cubes. The regression features are in Equation 7.

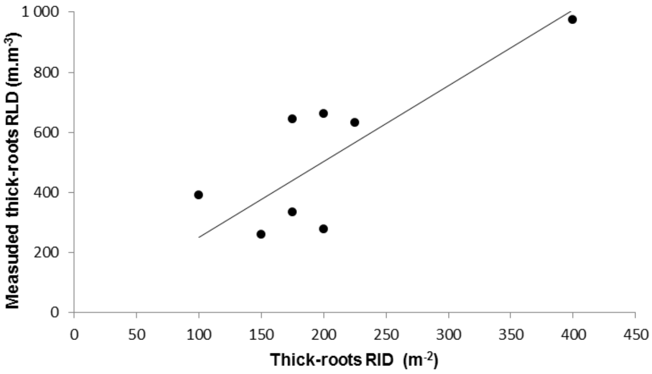

Figure 5. Calibration of the thick root model. Relationship between the observed number of intersections per m^2 (*RID*) and the measured root length density (*RLDm* in m m^{-3}) in the corresponding cubes. The regression features are included in Equation 8.

3.3.2 Thick roots

Empirical and geometric models: the thick roots in this data set were short (*table I*) and one sample had no roots at all on two vertical sides of the cubes; consequently, it was not possible to develop a geometric model. A simple model was developed that established a direct relation between the root intersection density of the thick roots (*RIDt*) counted on the vertical sides of the cube and the root length density of the thick roots (*RLDt*) measured inside the cube. The linear regression (*figure 5*) between *RIDt* and *RLDt* led to Equation 8. Taking into account the methods of measurement and the variability of field data, the relation is acceptable.

$$RLDt = 2.52 \times RIDt \quad n = 8 \quad R^2 = 0.621 \tag{8}$$

3.4 Testing the models

3.4.1 All root data set

For the all root data set ($n = 22$), the geometric (Eq. 6) and empirical (Eq. 7) models we developed to estimate *RLD*

Table III. Model tests. Characteristics and analysis of linear regressions between measured and calculated root length densities (*RLDm* and *RLDc*, m m^{-3}) with the empirical and geometric models.

	Model	*n*	Mean	Slope	Intercept	R^2	MB^a %	NE^b	RMSE^c%
All roots	Geometric	22	15,562	0.989	–345	0.909	3.5	0.907	25.0
	Empirical	22	15,643	0.984	–345	0.908	4.0	0.906	25.2
Thick	Empirical	16	1,186	0.772	175	0.681	10.4	0.604	48.9

^{a}: *mean bias (%),* ^{b}: *Nash efficiency coefficient,* ^{c}: *root mean square error (%).*

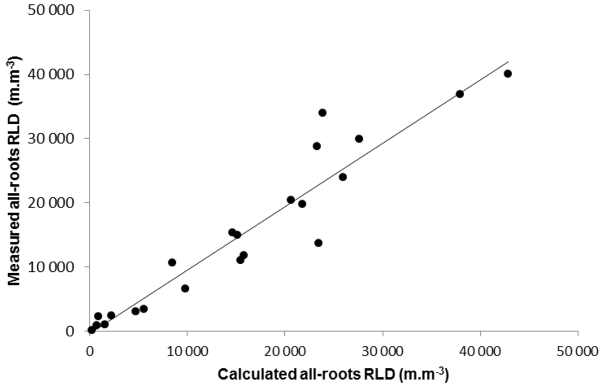

Figure 6. Validation of the all root model. Relationship between the measured root length density (*RLDm*) and the estimated root length density (*RLDc*) with the empirical model (*RLDc* = *RID*.4.48) for the all root data set between the surface and a depth of 60 cm (the regression features are listed in *table III*).

from *RID* were tested using an independent data set (different sites, different soils, different climate). The validation results are summarized in *table III* and *figure 6*. The two models satisfactorily estimated root length density according to the slope, intercept and R^2 of the regressions and other statistical quantities: the Nash efficiency coefficient, root mean square error and mean bias. The statistical quantities are close to models tested for upland rice: *bias* 3%, *RMSE* 37% *NE* 0.9 [11].

The empirical and geometric models gave very similar predicted values for *RLDc*, with root densities ranging from 200 to 45,000 m m^{-3} of soil, which correspond to average distances between roots 8.5 and 0.6 cm long, respectively.

3.4.2 Thick roots

The validation results are summarized in *table III* and *figure 7*. The empirical model provided a less satisfactory *RLDc* for thick roots than the one based on all root data. All the statistical quantities calculated confirmed this result, the slope, the intercept and R^2 of the regression and three other statistical quantities including the Nash efficiency coefficient, root mean square error and mean bias.

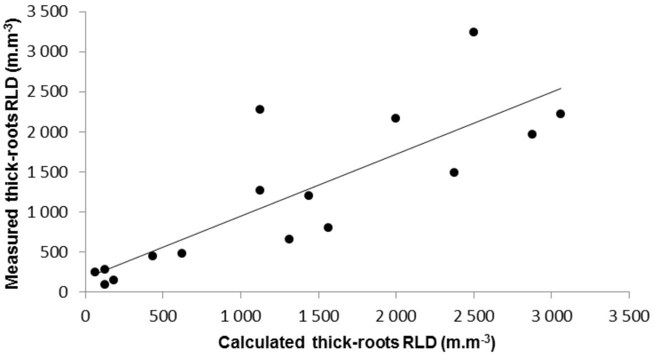

Figure 7. Validation of the thick root empirical model. Relationship between measured (*RLDm*) and estimated (*RLDc*) root length densities with the model (the regression features are given in *table III*).

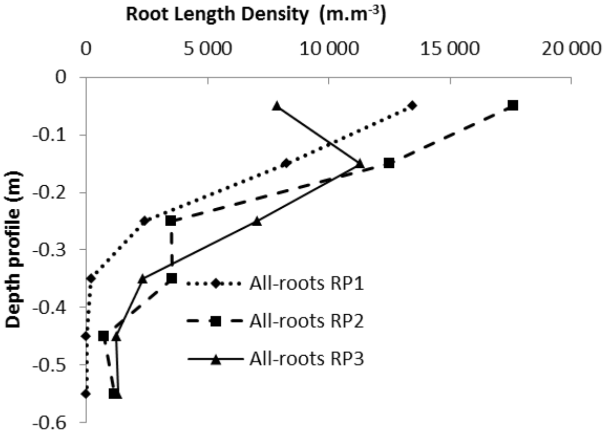

Figure 8. Vertical distribution of the root length density (*RLD* in m m^{-3}) in three profiles in the same field at Leyritz farm (RP1, RP2 and RP3) containing nine-month-old pineapple plants.

3.5 An example of the use of the model to describe RLD distribution in soil and its potential root extraction ratio (PRER) for water and nutrient uptake

As is true for most crops, the distribution of pineapple roots in the soil is not uniform but shows both vertical and horizontal gradients. Spatial variability is also related to the type of soil, the cultural practices and the level of parasitism [25]. This irregularity may disturb plant access to soil resources. Nevertheless, root profiles are conventionally estimated from average *RLD* values in the different soil layers. Mapping root intersections using the trench-profile method with a grid to facilitate spatialized measurements [13, 14], combined with the model proposed above (Eq. 6), enabled the spatial estimation of *RLD* from *NI*. Data management for the calculation of spatialized *RLD* and mapping with the software Racine2 [15] made it possible to describe root profiles taking depth into account, as is the case with conventional methods.

The method was used to describe three soil profiles (90 cm wide by 60 cm deep) in three different ridges in the same field at Leyritz farm (*figure 8*).

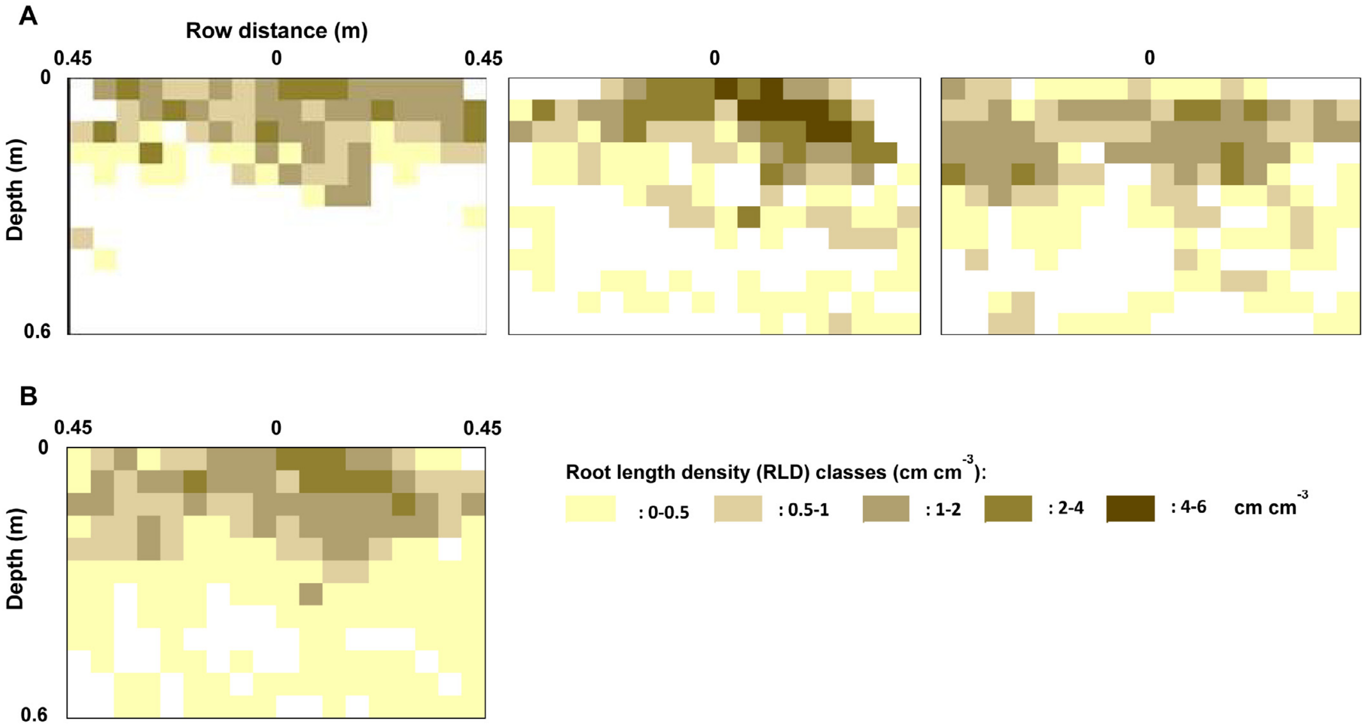

Figure 9. Mapping of root length densities (*RLD* in cm cm^{-3}). In the A maps, in three profiles in the same field (RP1, RP2 and RP3) containing nine-month-old pineapple plants at Leyritz farm. The B map below shows averaged values of RP1, RP2 and RP3. These maps represent profiles 90-cm wide and 60-cm deep. Each square cell measures 25 cm^2 and the maps were designed with the software Racines2 [15].

Root length density in the three profiles decreased with depth, with differences from one profile to another. The *RLD* in profile *R*3 was low between the surface and a depth of 10 cm but good below 20 cm. In contrast, in the *R*1 profile, the *RLD* was low at depth. This type of result allows a preliminary qualitative and quantitative analysis of the root system, but does not allow the comparison of gradients, heterogeneity and clumping at the same depth in the 3 profiles.

The mapping of root intersection densities (*RID*) and the use of the model proposed in this paper can describe the root systems through *RLD* maps (*figure 9*). These maps allow a visualization of the results of the *RLD* profiles depicted in *figure 8*. They can enrich the analysis of the distribution of the pineapple root system. On the maps, the variability of root profiles from one profile to another is spectacular. In all three profiles, the horizontal variability was quite large, including places without any roots between the surface and a depth of 20 cm. The greatest root density close to the surface (0–20 cm) was measured in profile *R*2 in which some areas had more than 4 cm of roots per cm^3 of soil, which is high. However, the distribution of roots in this profile was more heterogeneous. The *R*3 profile had the lowest *RLD* at the soil surface, but the distribution was fairly regular at depth.

The map obtained from the average *RLD* of the three profiles (*figure 9B*) is complementary to the map in *figure 9A*. The average of three values (for RP1, RP2 and RP3 in the A figures) reduced the heterogeneity of root distribution. Between 0 and 30 cm in depth, practically no more 25-cm^2 cells without roots were observed. Information on the spatial variability of the root system was lost, but the average gradient and a limit at a depth of about 25 cm was clearly visible. In this case, the limit corresponded to a change in the physical state of the soil, but it could have had other causes.

The information provided by the *PRER* is different from – and complementary to – the information provided by the *RLD* (*table IV*). Thus, in profile *R*2, (i) in the 0–20 cm soil layer, the *RLD* was 36% higher than the *RLD* in profile *R*3, whereas the *PRER* was 7% lower; (ii) in the 20–40 cm and 40–60 cm layers, the *RLD* represented, respectively, 23% and 6% of the *RLD* in the 0–20 cm soil layer, whereas the *PRER* still represented 62% and 34%. To describe the quality of the root system and for a better understanding and modeling of its functional activity, this information may be more useful than the *RLD* alone.

4 Conclusion

This study provides new information on pineapple root orientations in the soil. Both thick and fine roots were shown to be relatively isotropic with a slight vertical orientation. This advances our previously limited understanding of the architecture of pineapple roots.

Models that correlate the root intersection density (*RID*) on a vertical profile and root length density (*RLD*) were developed and validated on the basis of these findings. The first model (geometric) used a *CO* coefficient and an experimental coefficient *CE*:

$$RLD = RID \times CO \times CE \tag{9}$$

Table IV. Comparison of averages of root length densities (RLD cm cm^{-3}) and their corresponding potential root extraction ratios (PRER %) at different depths in three root profiles (RP1, RP2, RP3). Maximal migrating distance for mineral elements from the soil to the roots = 2 cm.

Soil depth (cm)	Root traits	Root profiles		
		RP1	RP2	RP3
0–20	*RLD*	1.085	1.506	0.958
	PRER %	72	65	70
20–40	*RLD*	0.132	0.351	0.47
	PRER %	14	41	52
40–60	*RLD*	0.002	0.095	0.127
	PRER %	0.8	22	24

The second model came from a linear regression fitting the direct relationship between measured *RLD* and *RID*. Developing the geometric model required counting the *RID* on three soil planes. The two models gave similar estimations of *RLD*. They could be used to predict *RLD* in the field on the basis of *RID* measured on a single vertical plane. The two models are accurate enough for *RLD* estimates in the field, if the aim is easy data acquisition for the analysis of root distribution in a particular soil.

For studies of soil-crop relationships or water and nutrient uptake [2, 18, 19, 25], our models make it possible to map root intersections on a plane (*trench-profile method*) or in rhizotrons to determine both the root length density and its spatial variability, which are standard root parameters for water and nutrient uptake. Running this method is simple, it only involves opening a pit and counting root intersections on the soil profile by mapping them using a grid. Complicated and time-consuming standard procedures (sampling, root extraction, preparation and measurements of root length) are thus not required unless obtaining highly accurate results is the prime concern [14].

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Cite this article as: Jean-Louis Chopart, Lila Debaut-Henoque, Paul-Alex Marie-Alphonsine, Rémy Asensio, Alain Soler. Estimating root length density of pineapple (*Ananas comosus* (L.) Merr.) from root counts on soil profiles in Martinique (French West Indies). *Fruits* 70 (2015) 143–151.