Root Distribution Under Seepage-Irrigated Potatoes in Northeast Florida

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ABSTRACT

Much of commercial potato production in Florida is irrigated using sub-surface seepage irrigation. A perched water table is maintained during the season within 50 cm below the top of the potato ridge. Fertilizer placement is critical in this system to maximize plant uptake and to minimize leaching potential. Optimal placement of fertilizers is dependent on root distribution. The objectives of this study were to develop and test a new methodology to spatially describe potato root distribution as affected by nitrogen rate and irrigation system. Soil slices containing representative samples of the potato root system at full flowering were taken from plots fertilized with ammonium nitrate at 168, 224, and 280 kg N ha^{-1}. The proposed sampling methodology performed satisfactorily. Root length density (cm root cm^{-3} soil) and specific root length (cm root mg^{-1} root dry weight) were not affected by nitrogen rate, but were affected by spatial position in the soil profile. The highest root length density value (0.72 average) was observed within 12 to 15 cm of the seedpiece. Low root length density values averaging 0.036 were observed between 24 and 36 cm from the top of the ridge. Specific root length values indicated a relatively homogeneous root system in terms of the quantity of invested biomass by unit of root length except in the two central units below 24 cm from the top of the ridge where thickened roots caused significant lower values averaging 6.47 as compared with the average of 15.87 from the surrounding Units in the slice. Root thickening in deep apical roots suggested aerenchyma formation promoted by a combination of saturated soil conditions in the root zone caused by inappropriate irrigation management and soil compaction. Fertilizer placement under the seedpiece should be a good alternative to increase potato nitrogen uptake under seepage irrigation.

RESUMEN

La producción comercial de papa en la Florida es irrigada por percolación sub-superficial. Durante la temporada de producción el nivel freático se mantiene a 50 cm por debajo de la cima del caballón donde la papa ha sido sembrada. La localización del fertilizante es un punto crítico en este sistema para maximizar la absorción y minimizar el potencial de lixiviación. La localización óptima del fertilizante depende de la distribución de las raices. Los objetivos de este estudio fueron desarrollar y validar una nueva metodología para describir espacialmente la distribución de las raices de la papa bajo efecto de la dosis de nitrógeno y el sistema de irrigación. En plena floración de la papa fueron muestreados perfiles de suelo conteniendo muestras representativas del sistema radicular de parcelas fertilizadas con nitrato de amonio en dosis de 168, 224, y 280 kg N ha^{-1}. La metodología propuesta funcionó satisfactoriamente. La densidad de longitud de raíces (cm raiz cm^{-3} suelo) y la longitud radicular específica (cm raiz mg^{-1} peso seco de

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ADDITIONAL KEYWORDS: aerenchyma, root length density, soil compaction, *Solanum tuberosum* L., spatial correlations, specific root length

ABBREVIATIONS: RDW, root dry weight; RLD, root length density; RSAD, root surface area density; SDW, soil dry weight; SVOL, soil volume; SWW, soil wet weight; SRL, specific root length; SRSA, specific root surface area; TRL, total root length; TRSA, total root surface area

raiz) no fueron afectadas por la dosis de nitrógeno pero si por su posición espacial en el perfil del suelo. Los valores mas altos de densidad de longitud de raíces (0.72 en promedio) fueron observados en una zona de 12 a 15 cm circundando la semilla. Entre 24 y 36 cm de profundidad fueron observados valores bajos de densidad de longitud de raíces con 0.036 en promedio. Los valores de longitud radicular específica indicaron un sistema radicular relativamente homogéneo en términos de la cantidad de biomasa invertida por unidad de longitud radicular excepto en los dos ambientes centrales por debajo de 24 cm de profundidad donde raíces engrosadas causaron bajos valores significativos promediando 6.47 comparados con el valor promedio de 15.87 observado en el resto de los ambientes estudiados. El engrosamiento apical en raíces profundas sugieren la formación de aerénquima promovido por la combinación de saturación del suelo en la zona radicular causada por manejo inapropiado de la irrigación, y compactación del suelo. La colocación del fertilizante debajo de la semilla de la papa podría ser una buena alternativa para incrementar la absorción de nitrógeno en condiciones de irrigación por percolación.

INTRODUCTION

Understanding the response of the potato root system to different production systems is critical to maximizing tuber production and quality. Pictorial descriptions of potato root system (Weaver 1926) and the effect of fertilizer placement and soil compaction (De Roo and Waggoner 1961) on root development have been previously reported. However, research reports on the relationships between potato plant root characteristics, water use, and uptake of nutrients are limited.

Enhanced nitrogen (N) uptake is a possible strategy to minimize nitrate leaching. In the short term, this could be accomplished by timely and precise placement of the fertilizer at soil depths where it could be quickly and efficiently absorbed by the roots. In the long term, the development of potato cultivars with high uptake and use efficiencies could be part of the solution to nitrate leaching from potato fields (Errebhi et al. 1998). In both cases, a detailed knowledge of the root system is required. Precise placement of fertilizer in time and space is especially important for nutrients such as nitrate that have high mobility in the soil. Root distribution studies are important to enhance the understanding of nutrient and water uptake in order to improve irrigation and nutrient management programs (Asfary et al. 1983).

In northeast Florida, nitrate leaching from agricultural crops has been considered as one of the possible causes for eutrophication of surface waters in the St. John's River watershed. Seepage irrigation, by raising the natural perched water table, is a common irrigation practice used for potato production in northeast Florida. The effects of saturated soil conditions created by the ascendant water flow from the water table on potato root systems and related consequences on nitrate uptake are still unknown, and therefore improved knowledge about the potato root system under these unique production conditions is needed to enhance N uptake and minimize the risk of nitrate leaching.

Previous research has used total root length (TRL) of potato in the field to calculate inflow rates of N, P, K, and water into the plant. Roots below 30 cm were more active in the uptake of nitrate and water than those nearer the soil surface under overhead irrigation (Asfary et al. 1983). In another study, two potato cultivars with differing N acquisition rates were used to demonstrate the importance of root length and root surface area over root dry weight in determining N uptake by the plant. A larger root system enabled one variety to absorb more nitrate when nitrate was limited, allowing for optimum yield compared with the second variety (Sattelmacher et al. 1990). However, these approaches may underestimate influx rate because not all root length and root surface area have equal nutrient uptake capacity. The region immediately behind the meristem has higher uptake activity than older segments although these segments maintain some uptake capacity (Gao et al. 1998; Robinson et al. 1991). Recent improvements in root characterization technology such as digital image analysis by specialized software have enabled roots to be analyzed in detail. Studies on potato root development (Pan et al. 1998), root architecture of pine (Danjon et al. 2000), root morphology of maize (Costa et al. 2002) and root architecture traits in common bean (Beebe et al. 2006) are good examples of the use of digital image analysis of roots. Root characterization studies have great potential to elucidate the role of root structure and root distribution in N management.

A study on potato root distribution was initiated to begin to understand root system development in seepage irrigation conditions. The experimental objectives were (i) to design and test a new methodology to obtain a representative sample from the potato root system in order to study vertical and horizontal potato root distribution, (ii) to study the effect of deficient, sufficient, and excessive N fertilization rates on the root distribution of the 'Atlantic' potato variety used extensively by the farmers in the Tri-County Agricultural Area (TCAA) located in the St. John's River watershed, (iii) to observe the effect of soil strength and bulk density on the potato root system under seepage irrigation, and (iv) to generate information that will help to enhance fertilizer placement to maximize N uptake and minimize leaching and/or runoff of nitrate from the potato beds.

MATERIALS AND METHODS

Site Description

The study was conducted during the potato season in spring of 2002 at the University of Florida/IFAS Plant Science and Education Unit, Hastings, Florida. The soil at the experimental site is classified as sandy, siliceous, hyperthermic Arenic Ochraqualf belonging to the Ellzey series (USDA 1981). The topsoil (1 m) texture is sand. Proportions of the particle fractions in the top 1 m are 94% sand, 2.5% silt, and 3.5% clay (Campbell et al. 1978). The soil profile has a sandy loam layer after 1 m deep. As a result, the profile is very poorly drained even though the saturated hydraulic conductivity in the top 1 m is about 10 cm h^{-1}. In its natural state, the water table is within 25 cm of the surface for 1 to 6 months in most years and slopes are less than 2% (USDA 1981). Weather data were continuously recorded at the research site through the Florida Automated Weather Network (FAWN; www.fawn.ifas.ufl.edu).

Crop Production Practices, Field Layout and Design

Potatoes were planted in 16 ridge beds (40 cm tall) flanked by irrigation-drainage furrows. Plots were randomized within an experiment designed to study the effect of nutrient management best management practices (BMPs) on four different crop rotation schemes (Munoz 2004) during the third year of the study. The BMP experiment followed a potato-sorghum-fallow rotation (traditional grower practice) under three potato crop N fertilization rates (168, 224, and 280 kg ha^{-1}). Potato (cv Atlantic) root distribution at full flowering, 60 days after planting (DAP), was measured. Munoz (2004) found that most of the sidedressed fertilization (40 DAP) remained in the soil surface and was leached to the water table during the rainy period in summer. Therefore, it was evident that N placement had negligible affect on root spatial distribution. At full flowering, Atlantic reaches its maximum vegetative growth and rooting depth (Stalham and Allen 2001). Over the course of the rotation experiment, the field was worked with bedder and chopper implements seven and five times, respectively. The last chopper pass was made to incorporate fertilizer prior to potato planting. Incorporating fertilizer so close to planting is not a traditional farming practice. However, it is part of the nutrient BMPs recommended for the region. A middle-buster plow was used just before the potato canopy closed to rip the compacted soil in the alleys to improve drainage. After the middle-buster pass, beds were hilled to reduce potato greening.

Ammonium nitrate (NH_4NO_3) was incorporated into the soil prior to planting (112 kg N ha^{-1}) and sidedressed at 40 DAP (56, 112, and 168 kg N ha^{-1}). Potato seedpieces (approx. 57 g) were planted at an in-row spacing of 20 cm and a between-row spacing of 102 cm, resulting in a crop density of 48,216 plants ha^{-1}. The irrigation method used was the semi-closed seepage system. This system is designed to maintain a constant water table level 50 cm below the top of the ridge. Soil moisture 20 cm under the ridge was visually checked regularly and the irrigation system was manually turned on if it was needed.

Plots used in the root measurement study were arranged in a randomized complete block design with three replications. Treatments were arranged in a split-split plot design with nitrogen rate assigned to the main-plot Unit (Munoz 2004), soil slice was the split-plot unit, and position in the soil slice was the split-split plot unit.

Root Sampling Methodology

A device to sample a representative portion of the potato root system was designed based on a sampler used by Vos and Groenwold (1986). The device, referred to as the "soil slicer," was composed of two sharp-edged galvanized steel sheets (thickness 2 mm), 101.6 cm long (distance between rows) by 50.8 cm in height (Figure 1a). Three wooden blocks kept sheets equi-distant from each other with an even separation of 10.2 cm (half the distance between plants). Three "C" clamps firmly held the pieces together (Figure 1a).

The soil slicer was hammered into the soil using a heavy wooden beam (Figure 1b) perpendicular to the soil surface (Figure 1c). Subsequently, that part of the ridge adjacent to the slicer was removed, the slicer containing the soil slice was flipped onto the ground, and the upper sheet was removed to access the ridge slice (Figure 1d). Each slice was split into

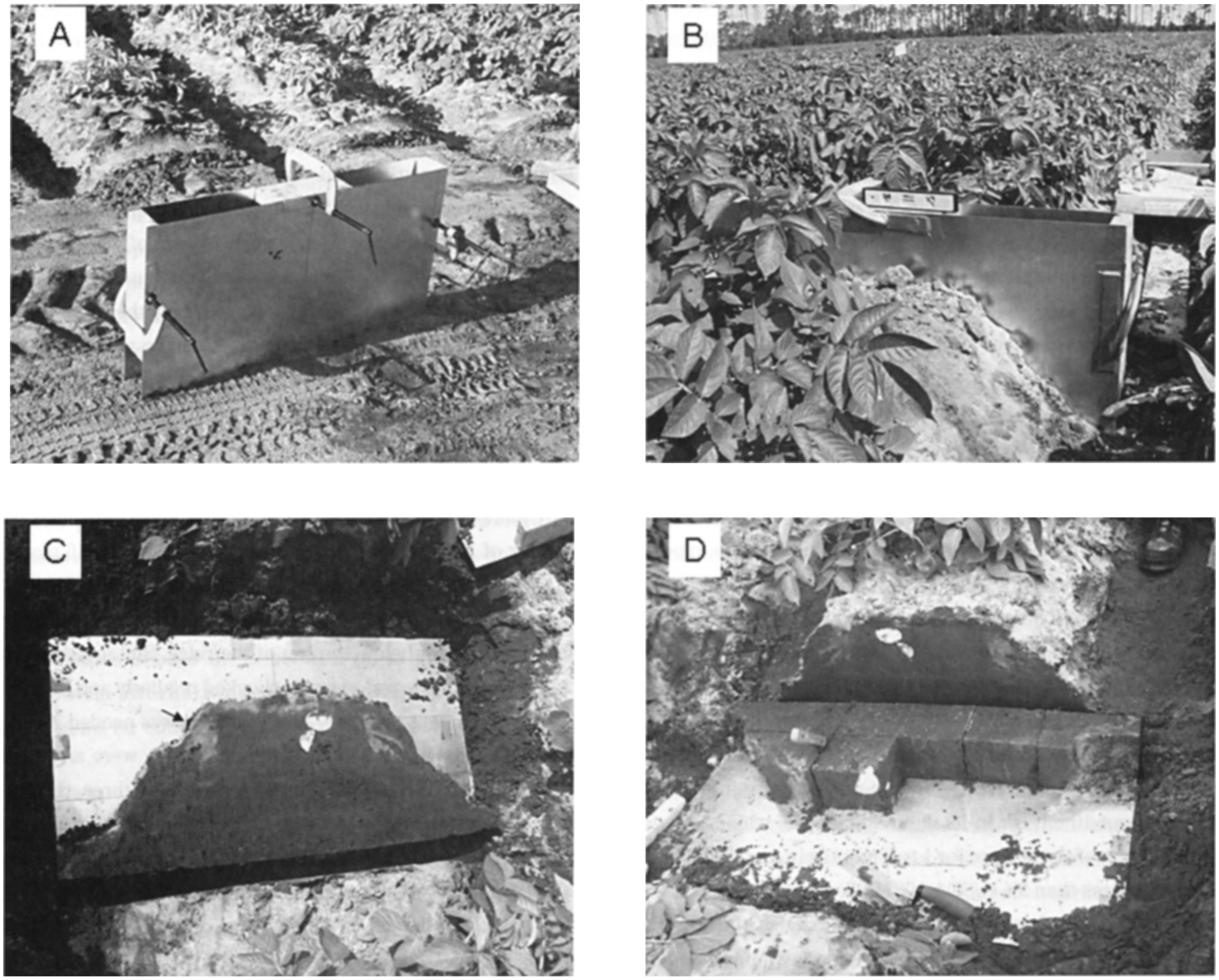

FIGURE 1.
Procedure to take the root samples: (a) root sampler; (b) leveled and buried into the ridge; (c) slice of the ridge; (d) splitting sub-samples.

three layers (top, middle and bottom) with each further split into units. The lower sheet had a pre-traced template with the dimensions of the units (sub-samples) on it. Using the template as guide, the dimensions of the units were traced on the surface of the soil slice. The slice was cut using a butcher knife, and each unit was then removed using a margin trowel. Each unit was placed in a plastic bag and coded by the first letter of the layer where it came from followed by a number to identify its position in the layer (Figure 2). Soil samples containing roots were weighed individually as soon as possible. Two slices, one including a plant and another one between plants, were taken in each plot.

Root Washing

Soil samples containing roots (units) were stored for a week in a cooler at 7 C until washed. Roots were separated from the soil by washing each unit on a screen (12 mesh = 1.5 mm) while removing large organic matter debris. Even with this "coarse' screen, the loss of tiny fragments of root was minimal given that the large size of each sub-sample (unit) allowed relatively long root segments to be retrieved. The washing process took a week. Afterward; root samples containing thin residues of organic matter were refrigerated in a preservative solution of sodium azide (0.01%). Shifts in root biomass due to respiratory losses were likely during the 2-week period from root sample collection until preservation with sodium azide. Subsequently, in the laboratory, roots were spread on white trays and sorted from thin residues of organic matter. This final sorting process took approximately 8 weeks.

Root Scanning and Image Analysis

Roots were stained by immersion in a solution of methylene blue (1 g L^{-1}) for at least 24 h, then spread on translucent Plexiglas trays containing water and scanned on a HP Scanner at a resolution of 300 dpi. Images acquired by this method were loaded and saved in Adobe PhotoDeluxe in PDD format. Root images stored as PDD were converted to grayscale BMP format prior to processing by GSRoot (Guddanti and Chambers 1993), a specialized software tool for root analysis. GSRoot was set up to classify roots by diameters and to estimate root length and surface area. Root scanning and image analysis was done in approximately 2 months by a technician dedicated exclusively to the process.

Root Variables

GSRoot was configured to measure seven diameter classes (<0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0, 1.0-1.2, >1.2 mm), to obtain root length and calculate surface area for the individual root diameter classes. The TRL (cm) and the total root surface area (TRSA) (cm^2) were calculated and reported as the total sum of length and surface area of the individual root diameter classes and expressed as meters of root per square meter of soil (m root m^{-2} soil) and square centimeters of root surface per square meter of soil (cm^2 root surface m^{-2} soil), respectively. The root length density (RLD) (cm root cm^{-3} soil) and the root surface area density (RSAD) (mm^2 root surface cm^{-3} soil) were calculated using the calculated SVOL for each sample (see next section). The RLD and the RSAD described the exploratory capacity of the root system in terms of length and surface area by unit of SVOL, respectively. High values of RLD and RSAD indicated high capacity of the root system to explore the soil.

Root samples were oven dried at 105 C after the scanning process until the weight was constant. Specific root length (SRL) (cm root mg^{-1} dry root) and specific root surface area (SRSA) (cm^2 root surface mg^{-1} dry root) were calculated in order to estimate resources invested by the plant for development of root length and root surface area for each unit of root dry matter. High values of SRL and SRSA indicate high efficiency of the root system in the assignment of resources. Total and marketable tuber yield of the plots were measured and analyzed in conjunction with all of the plots in the crop rotation experiment.

Soil Strength, Bulk Density, and NO_3^--N Concentration by Depth

Two days before root sampling, a Delmi penetrometer with a 30° cone-shaped tip was pushed 60 cm deep into the soil as measured from the top of the ridge in each sampled plot. Measurements were taken in the same ridge where roots were sampled. The penetrometer provided a continuous plot of soil strength (MPa). Undisturbed soil samples from each plot were collected at 12, 24, and 36 cm below the top of the ridge and used to estimate soil bulk density and soil moisture content in each of the three layers of the soil slice. After the slicing process, additional soil samples from the adjacent soil profile were collected at multiple locations along each of the three layers to estimate their average NO_3^--N concentration. The SVOL of each of the 14 units (split-split sub-samples) composing each slice was calculated using their overall dry weight average and the overall soil bulk density average of the layer from which each of the 14 units was collected.

Statistical Analysis

Root sampler. The soil wet weight (SWW) of each unit recorded at sampling time and the estimated soil dry weight (SDW) from the bulk density sampling were used to estimate the unit SVOL. The average SVOL of slices and unit values were used to evaluate the performance of the root sampling device (slicing) and the unit splitting, respectively. Replication (bed) and slice-pair were analyzed as random effects and their contributions to the total variance of the dependent variables were estimated using a random effects general linear model as implemented in the VARCOMP procedure of SAS using the Maximum Likelihood method (SAS Institute 2004).

Roots. Scatter plots (SAS/GRAPH, SAS Institute 2004) of the studied variables were used to help identify possible associations from among the large number possible. Four different general linear mixed effects models (PROC MIXED, SAS Institute 2004) were implemented and examined: (i) a model that assumed a common pooled variance for all units, making no accommodation for spatial pattern at the unit level; (ii) a model assuming heterogeneous separate variances for each bed (replication) by N treatment, again making no accommodation for spatial pattern at the unit level; (iii) a model assuming a common pooled variance with spatial correlations among units; and (iv) a model assuming a common pooled variance with spatial correlation assumed for between slices and among units within slices. Furthermore, these same four models were re-evaluated using root dry weight (RDW) and SVOL as covariates. After the evaluation process, RLD and RSAD were analyzed using the model that assumed spatial correlations within and between slices (model iv). The SRL was analyzed using the model assuming heterogeneous variances and RDW as a covariate (model ii) and the SRA was analyzed with the model assuming spatial correlations within and between slices and RDW as a covariate (model iv). The LSMEANS option was used to perform means separation. The statistical significance of differences in model-derived treatment factor means (least squares means) for SRL and SRA responses was computed using t-tests and separated with the Bonferroni adjustment, and for SRL and SRA by the Fisher test with defining individual comparison differences significant at the $\alpha = 0.001$ level.

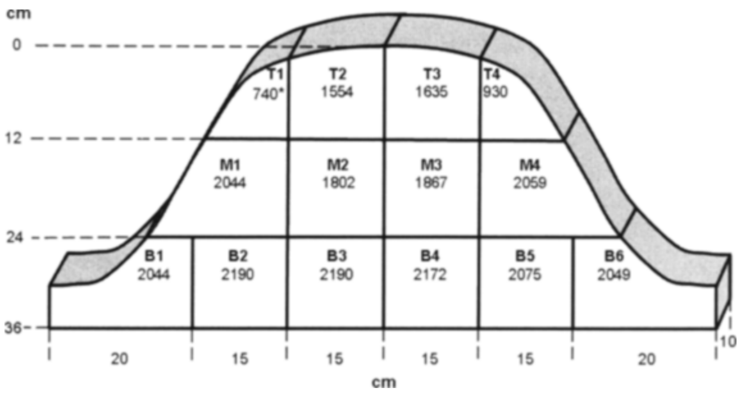

FIGURE 2.
Distribution and sample size in the slice. Soil volume (cm^3), dimensions (cm), T1 to B6 = unit code for identification. Soil volume values are the overall average across the sampled slices.

Soil Strength, Bulk Density, and NO$_3^-$-N Concentrations by Depth

Soil strength values obtained with the penetrometer and NO$_3^-$-N concentration by depth were analyzed using a general linear model for the split plot design (PROC GLM, SAS Institute 2004). Nitrogen rate was the main plot treatment factor and depth from 0 to 36 cm in increments of 12 cm from the top to bottom of the ridge was defined the subplot factor. Bulk density was analyzed as a randomized complete block design for the same depths sampled with the penetrometer. The statistical significance of differences in model-derived effects was computed using a t-test with Tukey adjusted significance levels. A regular Tukey multiple comparison test was used to separate soil bulk density means.

RESULTS AND DISCUSSION

Root Sampling Methodology

The slicing device and the methodology used to collect the root samples produced analyzable measurements with acceptable statistical properties. It was possible to cut perfect soil slices that subsequently were easily sub-divided into the above described units (Figure 2). The variance of the slice volume attributable to the sampling technique (slicing) was relatively low (365) compared with the variance of units (192.963) expressed as maximum likelihood estimates. The high variance for the units was possibly due to the irregular shape of the units around the outer edges of the slice (See arrow in Figure 1c) and to the variability resulting from cutting by hand the units in each slice. Average SVOL (cm^3) and horizontal and vertical dimensions for each unit are included in Figure 2. SVOL for each unit is the overall mean estimated across all the soil slices sampled.

Root Length Density and Root Surface Area Density

The statistical analysis revealed highly significant correlation between RLD and RSAD ($r^2 = 0.95$, $P < 0.0001$). For this reason, only the results from the statistical analysis on RLD are reported here. The high correspondence of RLD and RSAD on root distribution has been reported previously (Munoz 2004). No significant differences in RLD were observed under the three N rates applied to potato. Significant differences in RLD between units ($P < 0.0001$) and between soil slices ($P < 0.05$) are illustrated in Figure 3. There was no significant interaction between unit and slice. The soil slice containing the plant had higher RLD than the adjacent slice (Figure 3). The RLD values in units M2 and M3 were higher than all of the values observed in other units except for T2 and T3, where the difference was not significant. In the T2 and T3 units, adventi-

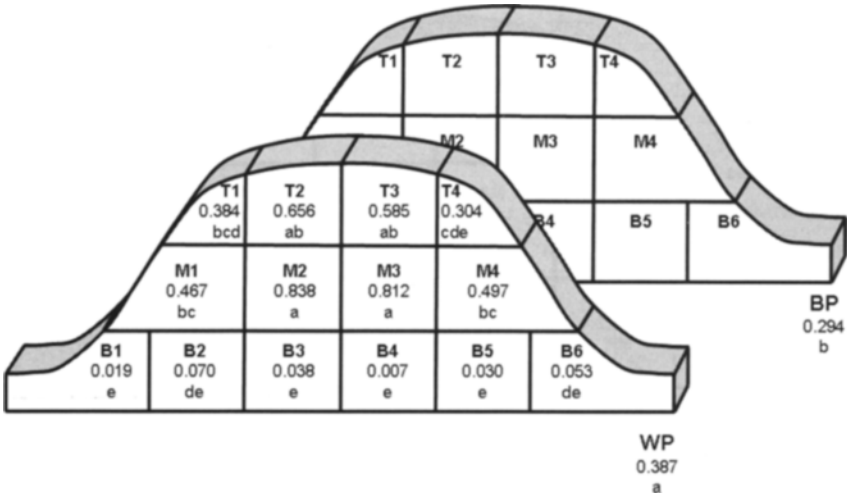

FIGURE 3.
Root length density distribution (cm root cm^{-3} soil). WP = soil slice containing the plant; BP = soil slice between plants. T1 to B6 = unit identification. Means with same lowercase letter are not statistically different. Units ($P <$ 0.0001); slices (<0.025). Means in each unit in the WP slice are the mean values across the units in the two different types of slices. Value reported under BP and WP is the mean value for the unit across the sampled slices.

tious roots originating from the stem when covering the emerged plants with loose soil at hilling, increased RLD values. Units M2 and M3, the seedpieces located at the origin of the potato root system (Figure 3) showed no differences. Units in the bottom layer (B1 to B6) had significantly lower values than units in the middle layer (M1 to M4), suggesting reduced soil exploration by cv Atlantic root system below 24 cm soil depth. (Figure 3).

Specific Root Length and Specific Root Surface Area

A highly significant correlation ($r^2 = 0.90$, $P < 0.0001$) between SRL and SRSA was found and for this reason only SRL results are reported here. The high correspondence on root distribution using SRL and SRSA was reported previously (Munoz 2004). There were no significant differences for slice or N treatment in SRL. Highly significant differences were detected between units. No significant differences were observed for the interactions between factors. Highest SRL values were observed in the T1 and T4 units which were not statistically different in average SRL (Figure 4). The high SRL values in the T1 and T4 units are an indication of numerous fine roots in this part of the ridge. Covering the emerged plants with loose soil at hilling (40 DAP) could explain the development of a system of fine adventitious roots in these units (Figure 4). On the other hand, the low SRL values observed in B3 and B4 (Figure 4) could be the result of an increase in root diameter caused by the combination of a high soil bulk density in B3 and B4 units and by capillary rise from the water table. Saturated soil conditions would increase root diameter by stimulation of aerenchyma formation (Drew et al. 1979), and saturated conditions would result from a higher capillary flux from the water table as reported in presence of a plow pan (van Loon and Bouma 1978). The higher SRL values observed in the units beside B3 and B4 suggest that the compacted zone in the subsoil immediately below the plants in the ridge is likely to be localized just inside the upper edge of M3 and M4. In terms of SRL, the T2 and T4 units contained the highest amount of fine potato roots. Both T2 and T4 are likely in regions where higher nutrient uptake occur assuming that soil moisture is not limiting at the top of the ridge. If RLD values (Figure 3) for T1 and T4 are compared with the values for M2 and M3 (Figure 3), the two units at the top of the ridge had significantly lower values than M2 and M3 in the middle of the ridge. This is also likely to be the results of higher concentrations of roots in the central units (M2 and M3) where the seedpiece is located. On the other hand, the significantly lower SRL values observed in M2 and M3 compared with T1 and T4 are an indication of the presence of thicker roots closer to the seedpiece. Generally, fine roots are more efficient in nutrient uptake because they have more surface area per biomass unit than coarse roots (Tinker and Nye 2000). Therefore the roots in T1 and T4 are expected to be more active in NO_3^- uptake under optimum soil moisture conditions.

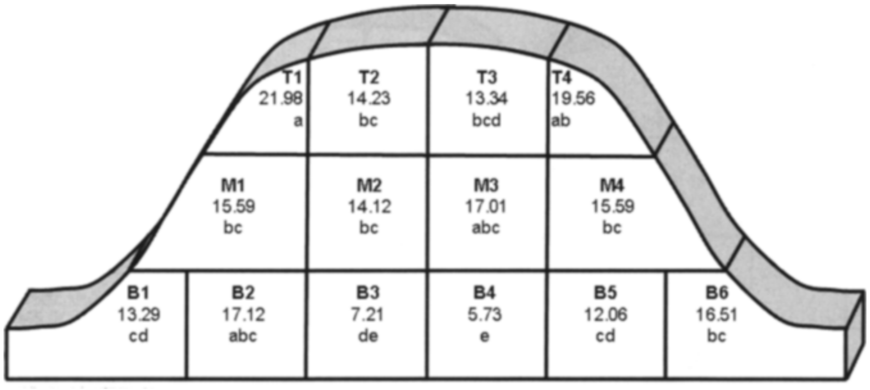

FIGURE 4.
Specific root length distribution (cm root mg^{-1} root dry weight). T1 to B6 = unit identification. Means with same lowercase letter are not statistically different ($P < 0.0001$). Values in each unit are the mean value across the sampled slices.

Soil Strength and Bulk Density

Soil strength differences between blocks (beds) were also observed. Nitrogen treatment had no effect on soil strength. Highly significant differences were observed among all of the three layers studied (Table 1). The increase of soil resistance from the top to the bottom layer coincided with a significant increase in the observed bulk density of the bottom layer compared with the top and middle layers (Table 1). In some root samples obtained from the 12 to 24 and 24 to 36 cm layers, a pronounced thickness of the roots was observed (Figure 5). A similar pattern of thickness has been reported for tomato roots impeded by a column of glass beads (Waisel 2002). Inhibition of main axis elongation and enhanced lateral root formation in young barley plants grown in fields with high bulk density also have been reported (Scott-Russell et al. 1974). Anaerobic conditions have been reported as a possible cause of aerenchyma formation in the root cortex of waterlogged maize (Drew et al. 1979), waxapple (Lin and Lin 1992), soybean (Bacanamwo and Purcell 1999), *Carex* species (Moog 1998; Visser et al. 2000), and *Hordeum* species (Garthwaite et al. 2003). For the potato roots reported here, a combination of these two conditions are likely responsible for the increase in root diameter for the middle and bottom layers of the studied soil profile (Figure 5). Increased capillary effect under moderate soil compaction conditions has been reported (Boone et al. 1978). Therefore, the moderate compaction values of this study could propitiate anaerobic conditions in the potato root zone promoting root swelling by aerenchyma formation (Figure 5).

TABLE 1—*Soil strength, bulk density, and soil NO_3^--N at each depth.*

Soil depth (cm)	Soil strength (MPa)	Bulk density (g cm^{-3})	Soil NO_3^--N (mg kg^{-1})
0-12	0.024 a	1.28 a	10.22 a
12-24	0.105 b	1.45 b	14.15 a
24-36	0.203 c	1.50 b	2.71 b

Soil strength ($P < 0.0001$); bulk density ($P < 0.0001$); soil NO_3^--N ($P < 0.0082$).

Soil NO_3^--N concentrations for the 24- to 36-cm layer was lower than the concentrations observed for the 0- to 12- and 12- to 24-cm layers. There was no difference between the two top layers (Table 1). The low concentration of NO_3^--N in the deepest layer can be explained by increased denitrification assuming anaerobic conditions occurred in the bottom layer, and/or upward capillary flux of water causing concentration of nitrate in the two top layers (Patel 2001).

Yield, Rooting Depth, Total Root Length, and Total Root Surface Area

Marketable yield was 19.7, 19.8, and 18.9 t ha^{-1} under 168, 220, and 280 kg N ha^{-1} respectively. The difference between N rates was not statistically significant.

The deepest roots were observed in the bottom layer (24-36 cm) and never exceeded 36 cm. This rooting depth is shallow compared with the maximum rooting depth of 60 cm reported for Atlantic on a deep sandy clay loam soil under overhead irrigation in the U.K. (Stalham and Allen 2001). In their study, Atlantic had the shallowest root system. The no-difference in RLD and SRL under N rates and the low marketable yield with no differences between N rates in our study

TABLE 2—*Root length and root surface area by diameter class and soil depth.*

Depth (cm)	Diameter class (mm)							
	<0.2	0.2-0.4	0.4-0.6	0.6-0.8	0.8-1.0	1.0-1.2	>1.2	Total
Root Length[a] (m root m^2 soil)								
0-12	93.38[a]	94.33	24.89	13.51	6.16	2.61	2.37	237.01
	39.4%	39.8%	10.5%	5.7%	2.6%	1.1%	1.0%	31.0%
12-24	142.93	219.92	69.30	25.51	12.03	5.77	5.29	481.23
	29.7%	45.7%	14.4%	5.3%	2.5%	1.2%	1.0%	63.0%
24-36	10.48	20.77	8.05	3.52	1.56	0.69	0.69	45.75
	22.9%	45.4%	17.6%	7.7%	3.4%	1.5%	1.5%	6.0%
Total	246.65	335.24	102.14	42.77	20.04	8.93	8.23	763.99
	32.3%	43.9%	13.4%	5.6%	2.6%	1.2%	1.1%	100%
Root Surface Area[a] (cm^2 root m^2 soil)								
0-12	25.82[a]	64.32	50.0	42.72	24.41	11.74	15.73	234.73
	8.7 %	27.4%	21.3%	18.2%	10.4%	5.0%	6.7%	28.0%
12-24	43.74	189.00	130.14	77.22	45.36	25.38	29.70	540.00
	8.1%	35.0%	24.1%	14.3%	8.4%	4.7%	5.5%	64.4%
24-36	3.88	21.65	16.62	10.00	5.54	2.67	3.44	63.68
	6.1%	34.0%	26.1%	15.7%	8.7%	4.2%	5.4%	7.6%
Total	73.14	274.99	196.62	130.03	75.37	39.41	48.86	838.41
	8.7 %	32.8%	23.5%	15.5%	9.0%	4.7%	1.0%	100.0%

FIGURE 5.
Potato root thickening observed in the trial.

suggests a restricted root system during the year root samples were collected (Munoz 2004).

The observed TRL for Atlantic in our study was 0.763 km root m^2 soil (Table 2). Although in the literature there are no data on TRL for Atlantic, it is very low compared with reported values as high as 24 km root m^2 for the cv Norin 1 (Iwama et al. 1999), 11.4 km root m^{-2} for cv Russet Burbank (Lescyznki and Tanner 1976), and even lower than 1.4 to 4.6 km root m^{-2} for cv White Rose (Bishop and Grimes 1978). The vertical distribution of TRL (Table 2) shows that Atlantic had 94% of the TRL in the two upper layers (0 to 24 cm), with 63% of the TRL concentrated in the middle layer (12 to 24 cm), and just 6% in the bottom layer (24 to 36 cm). The region from 12 to 24 cm may be the location of highest NO_3^- uptake under Hastings conditions. Seventy-six percent of the TRL was comprised of roots less than 0.4 mm in diameter suggesting this fraction was an important segment of the Atlantic root system (Table 2).

The observed TRSA for Atlantic was 838.41 cm^2 root m^2 with 92% of this area in the upper 24 cm of the ridge (Table 2) and 64.4 % in the middle layer (12-24 cm). The fraction of roots with a diameter less than 0.4 mm represented 76% of the TRL, but just 45% of the TRSA. This observation supports the cited limitation (Robinson et al. 1991) when TRL is used to estimate apparent nutrient influx rates. Determination of the root diameter class active in nitrate uptake will be a key factor to optimize fertilizer placement in order to improve uptake.

CONCLUSIONS

The designed root sampling device performed satisfactorily and was a good tool to study root systems for the northeast Florida potato-growing region. An improvement to the cutting process of units could be done by the using a template or a cutting board to equalize the volume of soil in the units. Nitrogen rates did not affect the root parameters evaluated; any change in N uptake should represent modification of the N uptake rate by unit of root surface and not due to changes in RLD or SRL. Placing fertilizer under or on top of the potato seedpiece should be the optimum if the objective is to get maximum uptake because RLD and SRL are maximum in these locations. Fertilizer placement at a depth of about 5 cm below the seedpiece for potatoes planted in beds would be another effective alternative, considering the ascendant water flux from the shallow water table management in seepage irrigated fields.

A more detailed study of the effect of saturated soil conditions and/or soil compaction on the potato root system will be needed to explain the potato root swelling reported in this study.

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