Ground penetrating radar (GPR) detects fine roots of agricultural crops in the field

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Introduction

To meet the world's growing demand for food, agricultural crop production is projected to double by 2050. It is widely accepted that breeding efforts focused on above-ground traits alone are not sufficient to achieve the projected yield goal and the shift of emphasis on the root system holds the hope. Yet a major limiting factor is the lack of efficient root phenotyping methods for use in the field. Ground penetrating radar (GPR) as a non-invasive technique is widely used in coarse root (>2 mm) detection. However, the applicability of the technique to detect fine roots of agricultural crops is unknown. The objective of this study was to assess the feasibility of utilizing GPR to detect fine roots under field conditions.

Materials and methods

This study was conducted in four locations in Texas (Amarillo, Uvalde, Dilley and Weslaco) with different soil types and soil moisture conditions (Table 1). Several cultivars of winter wheat and energy cane were scanned with GPR (1600 MHz). In each measurement transect, GPR antenna was moved at a steady speed over a 3-meter distance parallel to plant rows and between the two middle rows in each of the plots. Soil cores (5 cm diameter and 15 cm depth) were collected immediately after scanning. The soil cores containing roots were stored in a freezer (-20 °C) until processing. Root samples were separated from soil using a 0.15 mm sieve by washing and rinsing with water. Washed root samples were stored in plastic bottles with a 20% of ethanol solution and later the cleaned roots were scanned on a flatbed scanner and root diameter was analyzed with WinRhizo software ver. 2003b (Reagent Instruments Inc., Quebec, Canada). After scanning, roots were oven-dried until constant mass (75°C for 72 hours) and root dry mass was recorded.

Fig. 1 shows a raw GPR radargram and the steps to extract signal indices. Data processing was based on the methods of Butnor et al., (2003). Radar profile normalization, background removal and Hilbert transformation were processed with Radan 7 (GSSI, Nashua, NH, USA). All the profiles were converted to bitmap image files (*.bmp) and then analyzed with SigmaScan Pro 6.0 (Systat Software Inc., San Jose, CA, USA). To better compare the GPR signal against the measured root values (from the soil cores), radar profiles were sectioned with the most signal concentrated upper soil layer (0-15 cm) for further analysis. An intensity range of 140-200 was used to delineate the roots. Pixel number, intensity and total intensity within this threshold range were extracted. Average pixel intensity without threshold limit (0-255) was also used to compare with the different indices.

Regression analysis was conducted to identify the relationships between root traits and GPR signal using ordinary least squares regression, including uncertainty analysis. Analysis of variance with least significance difference was used to examine the significance among different varieties.

Table 1 Soil texture and moisture at 0-15 cm and field crops at the four Texas locations

Location	Soil texture	Relative soil moisture (%)	Crop
Amarillo	Silty clay loam	94% (76%)	Winter wheat (10 cultivars)
Uvalde	Clay	91%	Winter wheat (2 cultivars)
Dilley	Sandy loam	54%	Winter wheat (1 cultivar)
Weslaco	Sandy clay loam	41%	Sugar cane (7 cultivars)

Relative soil moisture is defined as the ratio of measured soil moisture divided by field capacity. The value of relative soil moisture in parentheses is from the non-irrigated field at Amarillo.

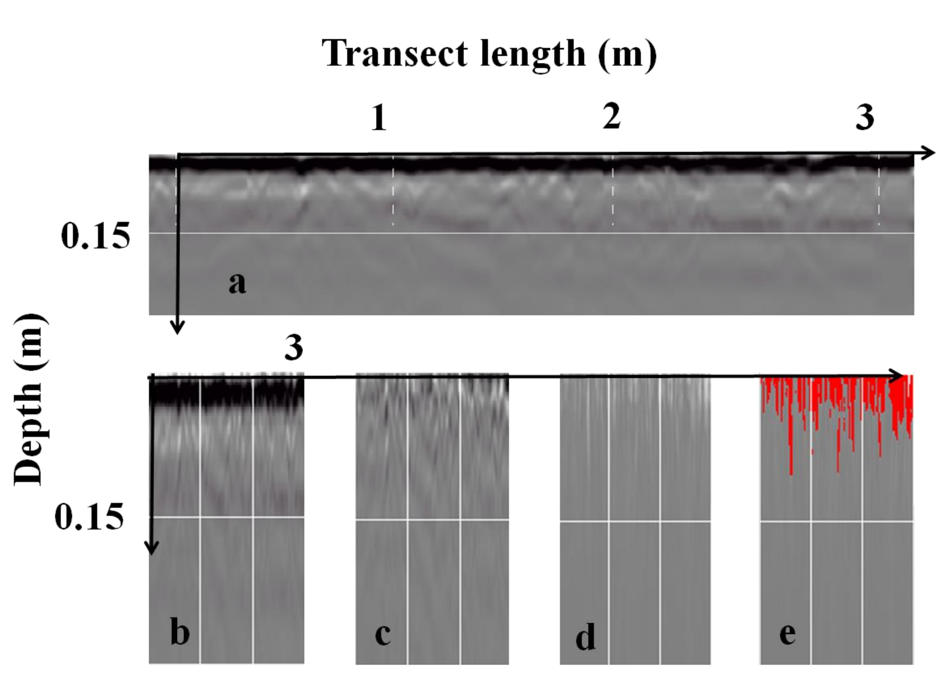
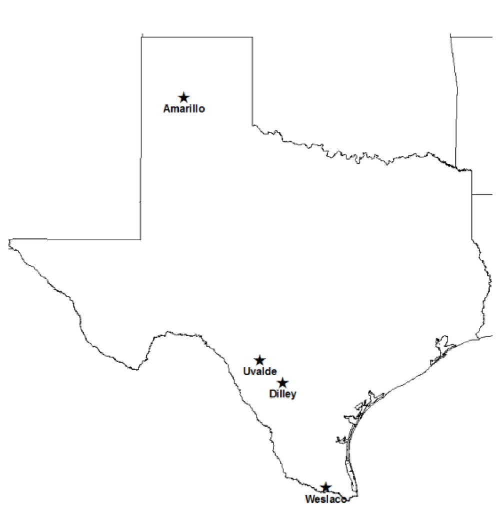
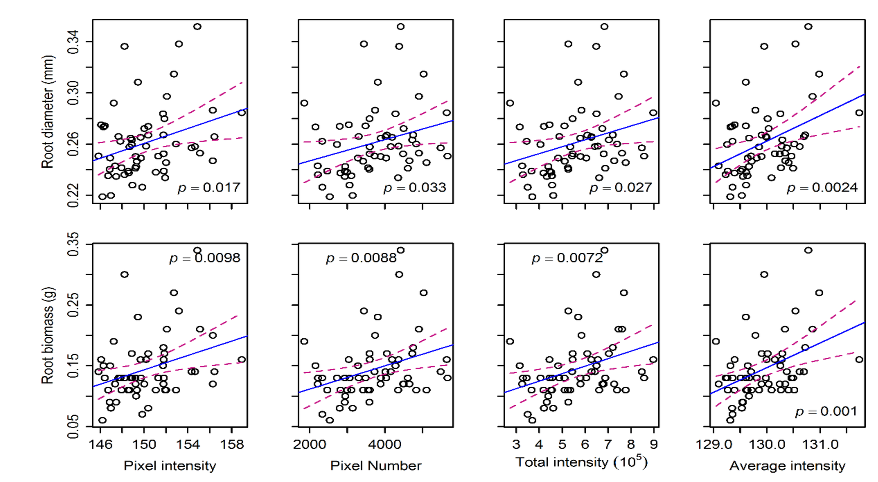


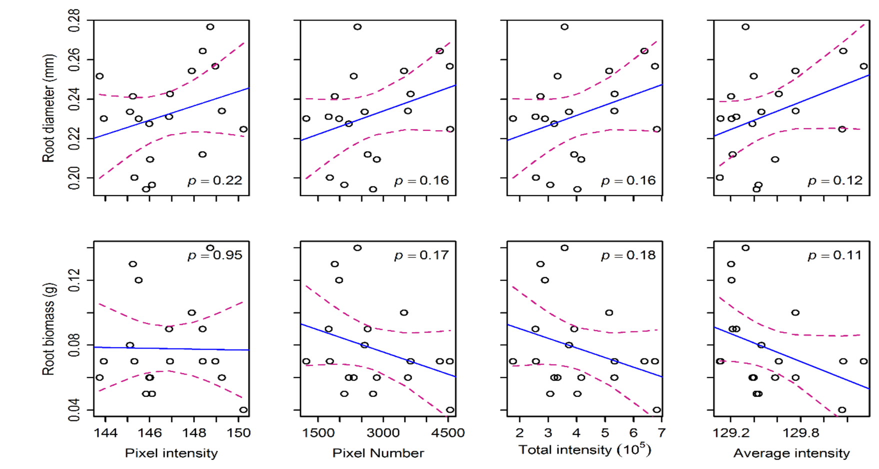
Fig.1 An example of GPR radargrams collected from winter wheat in the irrigated field at Amarillo. (a) Raw data from an SIR4000 GPR system with 1600 MHz antenna; (b-d) the same radargram processed in Radan 7 software after using distance normalization, background removal and Kirchoff migration to trace their sources; (e) the same radargram converted to 8-bit gray scale image, with the highlighted area in red color indicating pixels within the threshold range (intensity from 140 to 200) extracted with SigmaScan Pro 6.0 software. Vertical white lines indicate marks added when scanning the field and horizontal white lines indicate soil depth.



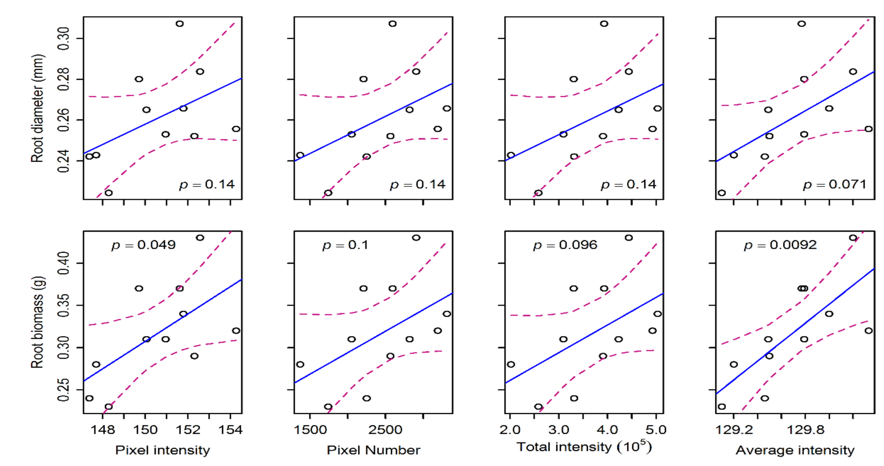
Results: Regression relationships between root traits and GPR signals



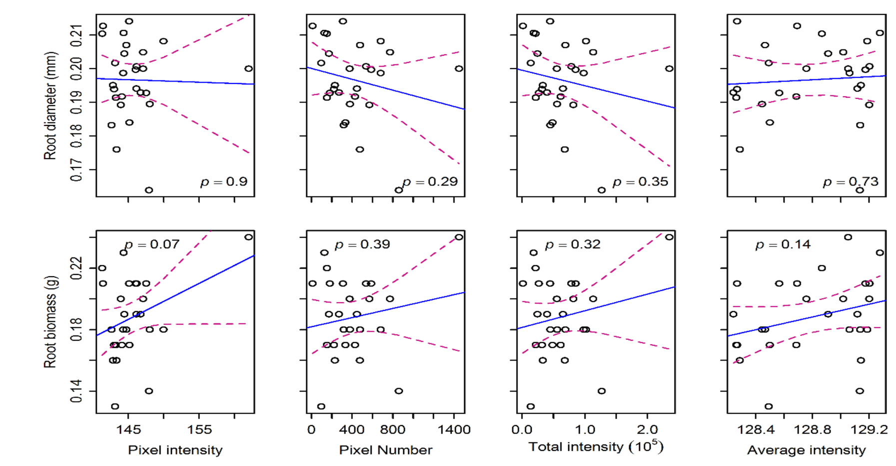
The irrigated field at Amarillo: significant



The dryland at Amarillo: insignificant

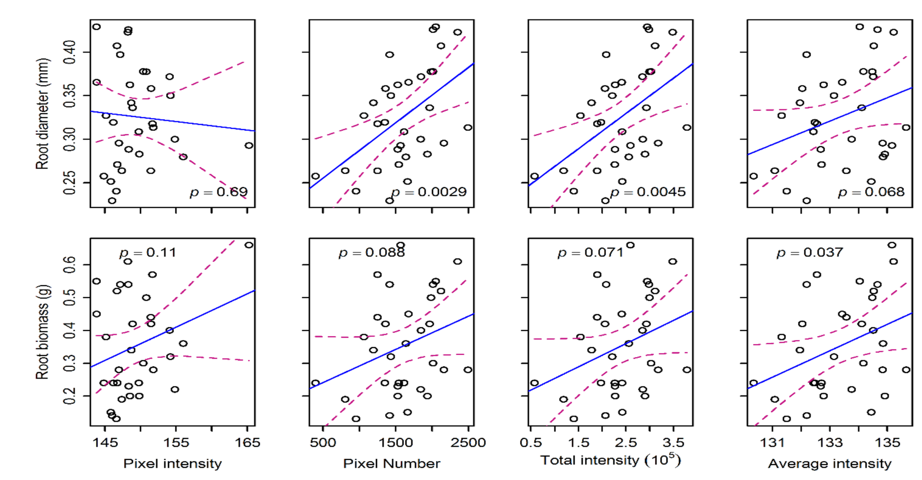


The irrigated field at Uvalde: significant and insignificant



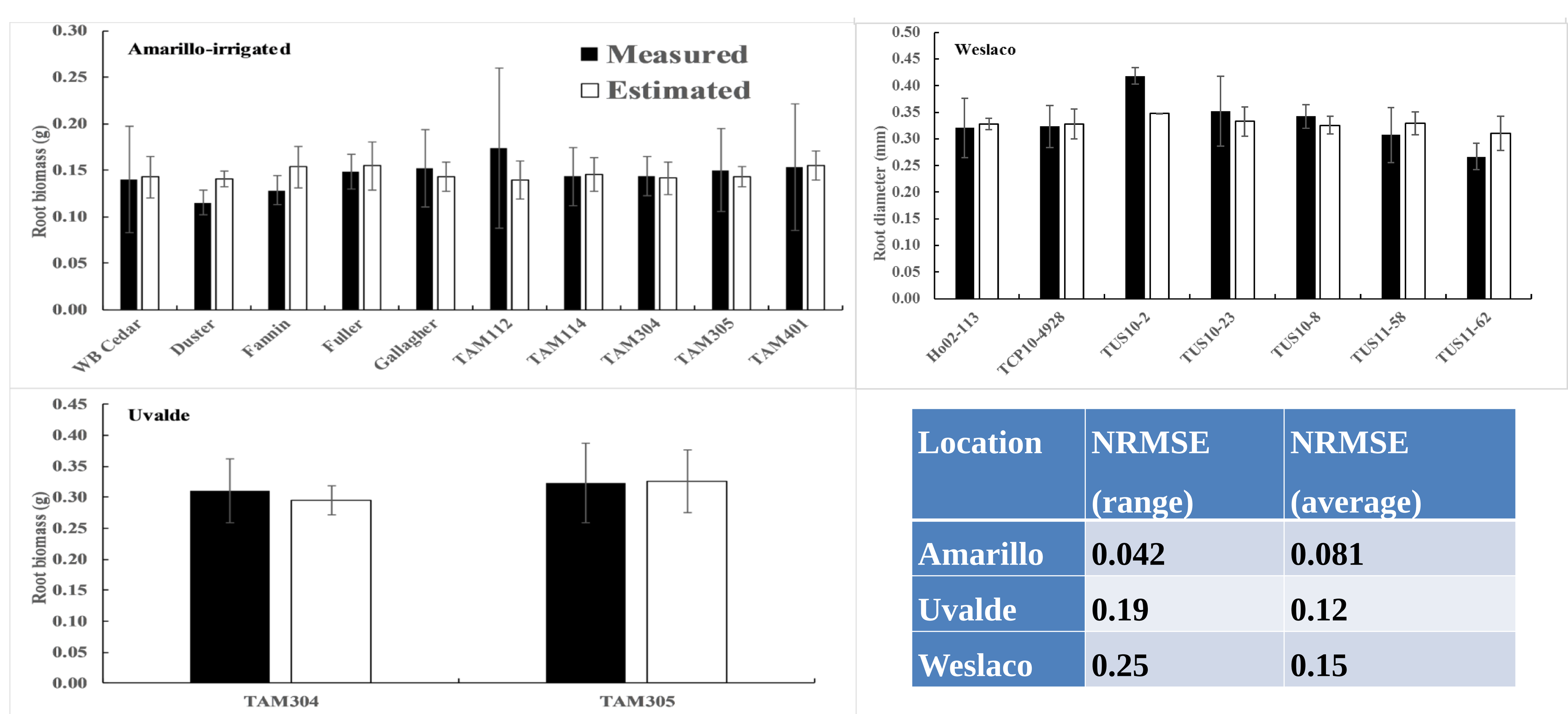
The dry field at Dilley: insignificant

Fig. 2 The relationships between root traits and GPR signal. *Significant relationships were found and the accuracy of root detection was higher in wet clay soils than in dry sandy soils. Average GPR pixel intensity without intensity threshold may be better to reflect root information than pixel indices with intensity threshold.*



The (dry) energy cane field at Weslaco: significant and insignificant

Results: Root character estimation



Location	NRMSE (range)	NRMSE (average)
Amarillo	0.042	0.081
Uvalde	0.19	0.12
Weslaco	0.25	0.15

Fig.3 Comparison of core-measured and GPR-estimated root parameters depicting the most significant relations for wheat (Amarillo, Uvalde) and sugar cane (Weslaco) cultivars. Normalized root mean square error (NRMSE) values were calculated from range and average of measured roots at the different test locations. 'range' indicates the difference between maximum and minimum values; 'average' indicates the mean value of all the measurements. *The best soil condition for detecting root traits using GPR is the silty clay soil with good soil moisture.*

Discussion and conclusions

- Both fine root diameter and biomass could be detected by GPR depending on soil conditions.
- Wet soils is more suitable for root detection with GPR than dry soil maybe because of the relative less soil moisture variation in wet conditions in the field.
- Average pixel intensity is more useful than other three pixel indices in quantifying fine roots.
- This is the first report showing the high potential of using GPR to detect fine roots in agricultural crops.

Reference:

Butnor JR, Doolittle J, Johnsen KH, Samuelson L, Stokes T, Kress L (2003) Utility of ground-penetrating radar as a root biomass survey tool in forest systems. Soil Sci Soc Am J 67: 1607–1615.