Field measurement of root density and soil organic carbon content using soil spectral reflectance

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Abstract
This paper summarizes the development of a proximal sensing technique used to predict root density, soil carbon (C) and soil nitrogen (N) content from the visible and near-infrared (Vis-NIR) spectral reflectance of soil cores. The techniques were evaluated at two sites in permanent pasture on contrasting soils (an Allophanic soil and a Fluvial Recent soil) and at two sites within a field of 90-day-old maize silage; Kairanga silt loam and fine sandy loam (Recent/Orthic Gley Soils) in Manawatu region, New Zealand. A portable field spectrometer with a modified soil probe was used to acquire reflectance spectra (350-2500 nm) from horizontal surfaces of soil cores. After scanning, thin soil slices were taken at each depth for root density measurement and soil C and nitrogen N. Calibration models developed using partial least squares regression (PLSR) between the first derivative of soil reflectance and the reference data were able to accurately predict the soil profile root density, and soil C and N concentration for all soils. Predicted root densities were not strongly autocorrelated to soil C values, indicating that root density can be predicted independently from soil C. This research has identified a potential method for assessing root densities in field soils enabling study of their role in soil organic matter synthesis.

Key Words
Carbon, nitrogen, near infrared, root density, maize, pasture.

Introduction
Pasture rotations in mixed farming systems have long been known to build soil organic matter (SOM) and create desirable soil structural features for seedbed preparation, drainage and aeration. The amount of SOM in pastoral soil is closely related to net productivity of roots, which is determined by previous soil and pasture management history (Nie *et al*. 1997) and type and stage of growth of the pasture (Fisher *et al.* 2007). The patterns of carbon (C) sequestration in both arable and pasture soils correlate well to plant root density and turnover times (Rees *et al.* 2005). Deeper root systems have the potential to sequester carbon (Smith 2004) deeper in the soil profile, where root turnover times can be slower. Organic carbon stored deeper in soil can slow the return of CO_2 to the atmosphere. Soil organic carbon stored deeper than 0.2 m and below 2 m can have residence times of 1000-2000 and 9000-13 000 years, respectively (Follet *et al.* 2003). There are other desirable features of deeper rooting plants. Plants with deeper, denser root systems have the potential to increase water use efficiency by optimising the use of subsoil water, and to recapture nitrate that would have leached past shallower root systems (Crush *et al*. 2007; Dunbabin *et al.* 2003). To exploit these opportunities crop cultivars that express deeper and denser rooting characteristics will need to be identified and then evaluated in field trials. Current common methods of measuring root density are the profile wall (Böhm 1979) and soil corer methods (Escamilla *et al.* 1991). Both require separation of roots and soil, which is a tiresome procedure, followed by root length measurement by the line intersect method (Newman 1966). Recently (Kusumo *et al.* 2009) used Vis-NIR reflectance spectroscopy to successfully predict, ryegrass root density in a glasshouse experiment. Sophisticated software (multivariate analysis) has allowed, reflectance spectra from soil to be calibrated against measured soil properties and the calibrations used to simultaneously predict several soil properties, such as total C, organic C (e.g. Chang and Laird 2002, Kusumo *et al.* 2008), total N, CEC and moisture (Malley and Martin 2003). Plants roots contribute directly to the reflectance bands associated with water and organic matter but roots as an intrusive property of soils mask other chromophores, such as, hydrous iron and aluminium oxides, and clays In this paper we summarize our recent research into improving the ability to predict root density in pasture and cropped soils from Vis-NIR spectral reflectance acquired from soil cores in the field.

Methods
Sites, soils and vegetation
The pasture root density assessment was undertaken at two permanent pasture sites (23.5 km apart): the first

on Ramiha silt loam (Allophanic soil, Andic Dystrochrept derived from loess and andesitic ash) and the second on Manawatu fine sandy loam (Fluvial Recent soil, Dystric Fluventic Eutrochrept derived from greywacke alluvium) in the Manawatu region, New Zealand (Hewitt 1998). The permanent ryegrass (*Lolium perenne* L) and white clover (*Trifolium repens* L) dominant pastures at both sites had been present for more than 20 years. The maize root density assessment was conducted on the day of harvest of a 90 day old maize crop. Two sites on the Kairanga soil series (Recent/Orthic Gley Soils) were chosen in the same field. At one site, the soil was dominantly silt loam and at the second site fine sandy loam in texture.

Acquiring spectral reflectance

At the pasture site a total of 18 soil cores, 10 m apart from each other, were collected from each site and cut into three depths (at 15, 30 and 60 mm), providing 54 samples at each site and a total of 108 soil samples. Reflectance spectra (350-2500 nm) were acquired *in situ* from the freshly cut surfaces using a purpose built soil probe attached by fibre optic cable to a field spectroradiometer (ASD FieldSpecPro, Boulder, Colorado, USA). A 3-mm soil slice (slice A) was collected at each surface, put in a sealed plastic bag and stored as field moist at 4^{o} C for no more than three days before root densities were measured using the wet sieve method (Kusumo *et al.* 2009). Root density was expressed as mg dry root g^{-1} dry soil. A further 3-mm soil slice (slice B) was collected; part was used for determining dry soil weight and soil moisture content (oven dry at 105^{o} C) and part was air dried and analysed for total C and N using a Leco FP-2000 CNS analyser (LECO Corp., St Joseph, MI, USA).

At each of the two maize sites, three replicate soil cores were taken at 0, 15 and 30 cm distance from the maize stem towards the centre of the 60 cm row. The distance between each replicate was 40 cm. A soil core was sectioned at 5 depths (7.5, 15, 30, 45, and 60 cm) and at each depth the soil reflectance spectra was acquired *in situ* as describe above. A 1.5 cm soil slice (slice A) was taken above the cut surface to obtain root mass reference data (using wet sieve laboratory root measurement). Another 1.5 cm soil slice (slice B) was taken air-dried and analysed for total soil C and N determinations and water content measurement.

Standing biomass

On the day of coring the pasture biomass cover was estimated to be approximately 1500kgDM/ha. Biomass data of maize stem and cob were collected one day before silage harvesting. Stem and cob dry matter values were obtained by drying them at 60^{o}C for 12 days.

Spectral data processing and statistical analysis

The spectral data were pre-processed (for details see Kusumo *et al*. 2009) and first derivatives of 5-nm spaced data calculated using SpectraProc V 1.1 software (Hueni and Tuohy 2006). The first derivative data were imported to Minitab 14 (MINITAB Inc. 2003) for principal component analysis (PCA) and partial least squares regression (PLSR) analysis. Prior to (PLSR) analysis, a PCA was conducted on the first derivative of the spectral data. A score plot of the first two components (PC1 and PC2) of the PCA analysis was used to select data for calibration and validation sets

Calibration models were developed by using PLSR to fit the reference data (root density, soil C and N) to pre-processed spectral data. The accuracy of the PLSR calibration models was tested internally by using a leave-one-out cross-validation procedure and when sample numbers permitted, externally using a separate validation sample set.

The best prediction models were shown by the smallest standard deviation of the difference between the measured and the predicted soil property values (RMSE, calculated from cross-validation is termed RMSECV and from separate validation is termed RMSEP) and the largest ratio of prediction to deviation (RPD), the largest ratio of the range of measured values of soil properties to the RMSE (RER) , and the largest r^2 (for more detailed explanation see Kusumo *et al*. 2009)

Results

Pasture soils

Mean root density decreased significantly with depth from 12.4 and 22.5 mg/g soil at 15 mm to 3.2 to 2.6 mg/g soil at 60 mm, both in the Ramiha and the Manawatu soil respectively. If the average amount of root mass in the 0 – 60 mm depth is expressed per hectare, the total root dry mass was 3642 and 9353 kg DM/ ha in the Ramiha (Andic Dystrochrept) and the Manawatu soil (Dystric Fluventic Eutrochrept), respectively, consistent with the result reported by Nie *et al.* (1997).

Soil C also decreased with depth from 10.2 and 4.5 % at 15 mm to 6.2 and 2.1 % at 60 mm, in the Ramiha and Manawatu soil respectively (Table 1). Interestingly, Ramiha soil with smaller root densities contained larger amounts of soil C. This is probably because SOM decomposition was inhibited by complexation with the amorphous clay mineral allophane (Boudot *et al.* 1988) which is abundant in this soil (Theng *et al.* 1986).

The PLSR calibration models of first derivative spectra and reference data for both soils were strong (r^2 > 0.99) and produced accurate predictions of root density in the validation set (Figure 1). Similarly soil carbon was accurately predicted in the Ramiha (r^2 = 0.86, RMSEC = 0.33, RPD = 2.73 and RER = 12.06) and Manawatu (r^2 = 0.86, RMSEC = 0.22,RPD = 2.64 and RER = 10.41). In the Ramiha soil root density and soil carbon were not autocorrelated (r^2 = 0.02) but in the Manawatu soils they were (r^2 = 0.73).

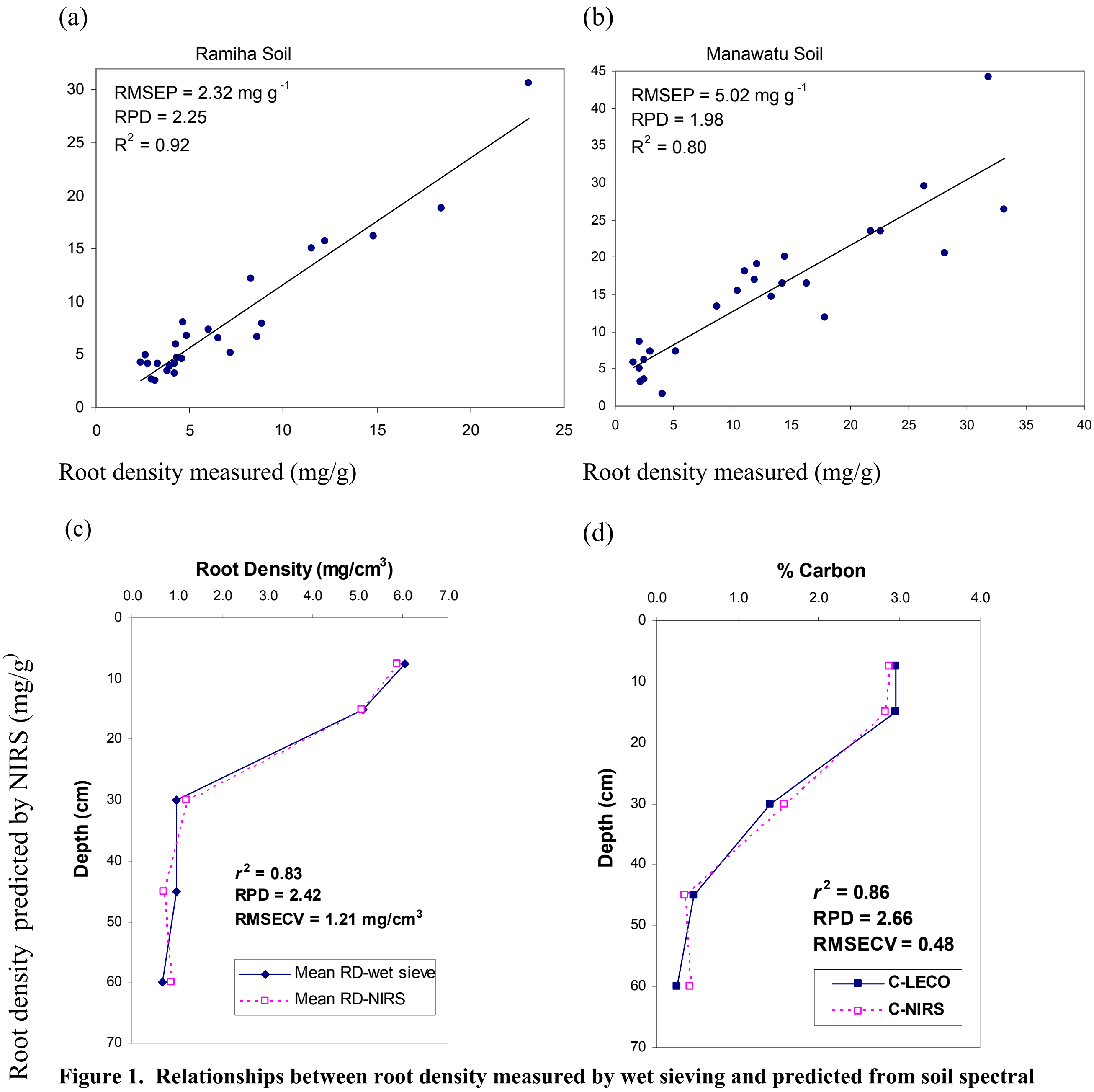

Figure 1. Relationships between root density measured by wet sieving and predicted from soil spectral reflectance created by separate PLSR calibration and validation data sets (a & b) for pasture soils, and measured (solid line) and predicted (dashed line) maize root density (c) and soil carbon (d) with depth for both soil textures

Maize soils
Root density (Figure 1c) was higher in the top soil (15 cm depth) and decreased with depth and decreased with distance from the plant stem (in the silt loam soil) but in the fine sandy loam, highest root densities were found 15 cm distance from the plant stem (data not shown) . Soil carbon also decreased with depth (Figure 1d). Both root density and soil carbon were accurately predicted from the PLSR calibration model developed using the first derivative of soil spectral reflectance (Figure 1 c & d). Root density could be predicted independently of soil carbon (data not shown).

Conclusion
Our results show that Vis-NIR spectroscopy can be used for prediction of pasture and maize root density and soil carbon in the field. Accurate PLSR calibration models can be developed from a small calibration set of field-acquired spectra from a soil slice with known reference root density and soil carbon data. The calibration models can be used to predict the carbon and root densities in a larger population of acquired spectral data. This approach can reduce the number of samples that must be measured for root density and soil carbon, especially when dealing with large sample sets (e.g. for mapping purposes).

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