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Tracking the influence of controlled traffic regimes on field scale soil variability and geospatial modeling techniques

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ABSTRACT

The employment of controlled traffic farming (CTF) can yield improvements to soil quality attributes through the confinement of equipment traffic to tramlines with the field. There is a need to identify how soil property variability and spatial modeling techniques are influenced by the inclusion of controlled traffic regimes at the field scale. Soil properties such as available nitrogen (AN), soil pH, soil total nitrogen (STN), soil organic carbon (SOC), bulk density, macro pore volume, soil quality S-Index, plant available water capacity (PAWC) and unsaturated hydraulic conductivity (K_m) were analyzed and compared among different positions within the traffic regime across two annual cropland sites actively employing CTF. The inclusion of tramlines displayed significant worse soil physical conditions when compared to un-trafficked soils while subsequently displaying minimal changes in soil nutrient properties. Furthermore, we contrasted regression models with ordinary geostatistical methods, such as ordinary kriging (OK) as well as the hybrid method of covariate kriging (COK) and regression kriging (ROK) to predict if the spatial distribution of soil properties in the field scale was altered from the traffic regime. The alteration of field scale bulk density, macro pore volume, S-Index and PAWC within the tramline soil caused consistent homogeneity within the area and direction of equipment traffic; however, these linear features were unable to be displayed through our ordinary geostatistical modeling methods and only somewhat captured using the ROK method. Alternately, AN, pH, STN, SOC and K_m observed to vary primarily as a function of landscape. This resulted in the addition of light detection and ranging derived terrain covariates with the COK method improving the field scale prediction and reducing uncertainty in the estimation of soil nutrient properties.

1. Introduction

The advent of precision agriculture, which was defined by Whelan and McBratney (2000) as “matching resources application and agronomic practices with soil and crop requirements as they vary in space and time within a field”, has been in part due to the access of economically viable global positioning systems (GPS). More specifically, univariate and multivariate geo-statistics have recently been applied to study the spatial heterogeneity of soil properties and compute predictive maps at both the field and regional scales (Baveye and Laba, 2015). The incorporation of geo-statistical analysis within precision agricultural systems has opened new windows of exploration into further refining farm management efficiencies. Desired improvements to resource use efficiencies have paved the way to controlling the layout of the traffic regimes within a field, which is defined as controlled traffic farming (CTF). This management system has been adopted in Australia and to some extent in Europe, as it has been shown to improve soil quality and aid in the recovery of soil structure (Chamen et al., 2015; McHugh et al., 2009). The implementation of CTF reduces the overall coverage and intensity of spatial compaction by restricting the movement of all farm equipment to permanently trafficked areas within the field, called tramlines (Tullberg et al., 2007). Reducing the field area which receives traffic induced compaction can improve key soil physical properties in the un-trafficked areas, such as bulk density, pore volume and unsaturated hydraulic conductivity (McHugh et al., 2009; Unger, 1996), as well as potentially reduce overall soil greenhouse gas emissions (Antille et al., 2015; Gasso et al., 2014, 2013). Thus, it is imperative to identify if tramlines in CTF regimes alter the variability of soil properties that are measured and used as indicators for further field scale optimization of resources.

Geo-statistics, in its early form, was used to accurately predict the grade of gold ore in South African mines (Krige, 1966), but within the past few decades it has become a common methodology that soil scientists have utilized to determine the spatial variability of soil properties. However, common geostatistical estimation methods, such as ordinary kriging (OK), may not be sufficiently adequate forms of

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prediction; hybrid methods, such as covariate kriging (COK) or regression kriging (ROK), may be necessary to properly define soil spatial structures (Heuvelink et al., 2016) and account for multiple spatial variability sources. Incorporation of covariates in the COK method have been shown to improve general model fit (Ceddia et al., 2015; Wang et al., 2013), while the use of ROK has been shown to have a better performance when compared to OK (Hengl et al., 2004; Maynard et al., 2011; Odeh et al., 1995) and COK (Knotters et al., 1995; Mirzaee et al., 2016; Simbahan et al., 2006). Moreover, the art of obtaining accurate realizations of the field scale spatial distribution of soil properties poses the question as to which method produces optimal spatial models in CTF environments.

Numerous studies have been completed worldwide on predictive mapping of the pedosphere and understanding the spatial variation of soil properties over regional scales (Huang et al., 2007; Li et al., 2014; Raczkowski et al., 2012). However, focus on field scale variability within agricultural settings has not been comprehensively covered (Alletto et al., 2010; Alletto and Coquet, 2009), particularly within controlled traffic regimes. As the optimization of field scale resources and the use of geostatistical methods to aid in that endeavor become more common in precision agriculture, understanding the effects controlled traffic regimes have on soil spatial variability can assist the development of more robust mapping tools (Qiu et al., 2016; Zhang et al., 2011). Furthermore, quantification about the performance of different methods of predictive mapping can inform decision making when creating future field scale spatial models that may be used for management zone delineation or soil survey in comparable landscapes and management practices. Thus, the objectives of our project were: (i) examine how the spatial structure of soil quality properties are influenced as a function of the controlled traffic regime, the landscape or a combination of both factors, and (ii) determine which geostatistical method yields the best goodness-of-fit and reduces the prediction uncertainty within the field scale.

2. Materials and methods

2.1. Study sites

Commercial sites that represented the current foci of soils used for global agricultural production were chosen based upon: (i) chernozem soils cover 230 million hectares worldwide (Deckers and Nachtergaele, 1998) and represent commonly used soil for commercial agricultural production throughout the Great Plains of North America and Eurasian steppe, and (ii) the propagation of new farming land commonly extends towards soils that are semi-arable or forested, such as those of the Luvisolic order. A 108 m × 110 m (11,880 m^2) plot was selected at commercial CTF study sites in a Dark Grey Luvisol (Dapp site, 54.402527° and −114.042741°) and Black Chernozem (Lacombe site, 52.490535° and −113.660029°), as each site implemented controlled traffic regimes in 2011 (Table 1). Clay minerology was similar between sites, with the clay fraction comprised of montmorillonite, illite and kaolinite (Pawluk, 1961; Plante et al., 2010). Annual spring cropping was conducted with differing crop rotations occurring at both sites; however, at the time of sampling both sites were planted with spring wheat (*Triticum aestivum* L.).

The management of CTF was similar across both sites, with sprayer tramlines left unseeded and tramline spacing occurring at 9 m accompanied by a center-to-center track gauge width of 3.05 m (120 in.). Typical techniques throughout the growing season in the North American Great Plains employ one-pass seeding, one to three pass seasonal spraying, one-pass harvesting and occasional post-harvest residue harrow or minimum tillage. Peak axle loads experienced from equipment at each site occur at either seeding time from the tractor (~9000 kg $axle^{-1}$) or at harvest time from the combine (~8500 kg $axle^{-1}$) and grain cart (~12,000 kg $axle^{-1}$); however, the majority of compaction experienced in these rainfed systems transpire during moist seeding conditions due to the exacerbating nature of soil moisture (Hamza and Anderson, 2005).

2.2. Sampling design and collection

The plot for each study site was located near the central point within each field and encompassed twelve sets of tramlines, each within a 9 m swath. Collection of the soil samples took place from 16 to 18 June 2015 at Lacombe and from 23 to 25 June 2015 at Dapp. The sampling procedure employed a cyclic sampling design (Fig. 1) as outlined by Clinger and Van Ness (1976), through which a cyclical variation in the sample grids were applied to capture maximum sampling efficiency (Bond-Lamberty et al., 2006; Loescher et al., 2014). A vertical sample spacing distribution of 0, 2, 8, 18, 38, 42 and 48 m from the first sampling point was repeated twice in each vertical row from the left to the right of the plot, with a 10 m offset from the first point applied to every second vertical row. The horizontal sample spacing for each vertical row was distributed by 0, 10, 40, 70, 100, and 110 m from the first vertical row, progressing from the top to bottom of the plot (Fig. 1). This sampling design enabled a minimum of 20 pairs for each 2 m lag distance class to be realized while simultaneously reducing a large accumulation of small scale lag pairs for sampling efficiency (Orr et al., 2014). However, to account for potential field scale interactions per swath, a nested sampling design (Fig. 1) was included within the larger cyclic sampling design. The nest was confined within a 9 m swath and was composed of four vertical rows of three sampling points spaced at specified distances. The overall sampling distribution allowed for sampling points to be compared between trafficked (tramlines) and un-trafficked areas. Additional categorization of the tramlines into intermediate tramlines (tramline without sprayer traffic) and sprayer tramlines (tramline with sprayer traffic) and was performed and contrasted against the un-trafficked areas.

Soil sample geographic coordinates and elevation values were recorded in universal transverse mercator (UTM) with an AgGPS 332 (Trimble® Inc., Sunnyvale, CA, USA) differential global positioning system (DGPS) and collected at a depth increment of 5–10 cm in the cyclic sampling design, yielding a total 72 sampling points. Additional samples were collected at depth increment of 5–10 within the nest, comprising of a total of 12 samples taken from the 12 nest sampling points. Collectively, 96 soil samples were obtained for each study site, as sample sizes substantially smaller than 100 samples are not recommended due to the potential for noisy variograms and uncertain calculations of the sill or autocorrelation distance (Oliver and Webster, 2014). Undisturbed soil core samples used for soil physical and hydraulic property analysis consisted of a stainless-steel soil core with an inner diameter of 8 cm and height of 5 cm (~250 cm^3 volume). Additionally, four push probe soil core samples (~150 cm^3 volume) were composited for soil nutrient analysis at the same depth increment and within 2 cm of the undisturbed soil core sampling point.

Table 1
Study site characteristics at the 5–10 cm soil depth for two controlled traffic farming (CTF) sites in Alberta.

Site	Year of CTF implementation	Soil great group classification	Soil texture	Clay (%)	Silt (%)	Sand (%)
Dapp	2011	Dark Grey Luvisol	Sandy Clay Loam	21.41	43.13	35.46
Lacombe	2011	Black Chernozem	Sandy Loam	10.77	30.98	58.25