Spatial distribution of soil mechanical strength in a controlled traffic farming system as determined by cone index and geostatistical techniques

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Abstract. Controlled traffic farming (CTF) is a mechanisation system in which all load-bearing wheels are confined to the least possible area of permanent traffic lanes and where crops are grown in permanent, non-trafficked beds. In well-designed systems, the area affected by traffic represents less than 15% of the total field cropped area. The extent and distribution of soil compaction at locations laterally outboard of the permanent traffic lanes may explain the performance of the crop on the rows located either side of the wheeling. This compaction is due to lateral displacement of soil caused by repetitive wheeling, the effect of soil-tyre interaction and the soil conditions (strength) at the time of traffic. The impact of compaction on crop rows adjacent to permanent traffic lanes is also dependent on the seasonal effect of weather, because of changes in soil water availability. This work was conducted to model the spatial distribution of soil mechanical strength under increasing number of tractor passes to simulate the soil conditions that may be encountered in CTF systems at locations near-permanent traffic lanes. The study was conducted on a *Typic Argiudoll* (26% clay, 72% silt, 2% sand) with four traffic intensities (0, 6, 12 and 18 passes) using a 120 HP tractor (overall mass: 6.3 Mg). Traffic treatments were applied to experimental plots using a completely randomized block design with three replications per treatment. The spatial distribution of soil strength within wheeled and non-wheeled zones was determined using a cone penetrometer (depth range: 0–300 mm) and geostatistical techniques. In all treatments, cone index showed a quadratic response with depth, which explained between 67% and 88% of the variation in soil strength. The number of tractor passes had no effect on the range of spatial dependence of residuals. No differences were observed in the proportion of grid cells where penetration resistance was greater than 2 MPa (considered to be the soil strength limit for root growth of most arable crops) between-traffic treatments, or wheeled and non-wheeled zones, respectively. The overall mean proportion ($\pm$ 95% confidence interval) of grid cells (4.9 $\pm$ 4.5%) suggested that this measure has a relatively high variability and therefore may not be a reliable parameter to be used in the design of future experimental work.

Key words: field traffic, soil compaction, soil mechanical properties, soil penetration resistance.

INTRODUCTION

The development and adoption of higher capacity, and therefore heavier agricultural vehicles, raises concerns over the long-term sustainability of intensively-managed arable cropping systems, because of increased potential for deterioration of soil structure due to traffic compaction (Chamen et al., 2003; Spoor et al., 2003; Keller et al., 2019). In permanent (e.g., > 15 years) zero-tillage (ZT) systems without controlled traffic, compaction may aggravate other soil degradation processes (e.g., erosion, runoff, loss of soil organic carbon), which may be conducive to reduced crop productivity and increased the risk of greenhouse gas emissions (Soane & van Ouwerkerk, 1995; Li et al., 2007; Antille et al., 2015a). Studies conducted in Argentina have shown that long-term ZT systems often exhibit widespread soil compaction (e.g., Díaz-Zorita et al., 2002; Antille et al., 2015b; Masola et al., 2020). This is explained by relatively high traffic intensities (≥ 40 Mg km^{-1} ha^{-1}) commonly observed in those systems (e.g., Botta et al., 2007; Mašek et al., 2014). The effects of traffic-induced compaction are often persistent (e.g., > 5 years), particularly in the subsoil (Spoor, 2006; Radford et al., 2007). In intensively-managed soils (e.g., double-cropping) under ZT, these effects are exacerbated by the frequency of traffic, which therefore restricts the opportunities for soil repair through natural processes (Dexter, 1991). Soil mechanical resistance influences root penetration into the soil, and exploitation of soil water and nutrients by the plant, thereby affecting crop growth and yield (Goss, 1977; Letey, 1985; Lipiec & Stępniewski, 1995). Soil penetration resistance is widely used to determine soil strength both under field and laboratory conditions (e.g., Ayers & Bowen, 1985; Nawaz et al., 2013; Rooney & Lowery, 2000). Increased soil strength above a critical value of 2 MPa (suggested limit value for most arable crops) at soil water contents near-drain upper limit severely restricts root elongation (Taylor & Gardner, 1963; Carter & Tavernetti, 1968). Controlled traffic farming (CTF) systems are regarded as a practical and cost-effective technology to minimise the impact of field traffic-induced soil compaction (Kingwell & Fuchsbichler, 2011; Chamen et al., 2015). The underlying principle of this technology is the establishment of two distinctive zones within a field; namely: permanent crop beds (non-wheeled soil) and permanent traffic lanes (wheeled soil), respectively (Taylor, 1983; Tullberg et al., 2007). Both anecdotal and reported evidence indicates CTF systems to have positive impacts on crop productivity, and importantly on resource use-efficiency, particularly water (rainfall and irrigation), fertiliser and on-farm energy use (Hussein et al., 2018; Bluett et al., 2019; Tullberg, 2000). Acknowledgement of these benefits has been the main driver for increased adoption of this technology (Tullberg et al., 2007; Chamen, 2015), although at a much slower rate in some cropping systems (e.g., Braunack & McGarry, 2006; McPhee & Aird, 2013; Antille et al., 2016).

Only few studies available in the scientific literature have investigated the spatial variability of soil penetration resistance as affected by vehicular traffic at the field-scale; these studies include 2D and 3D approaches (e.g., Castrignano et al., 2002; Ferrero et al., 2005; Carrara et al., 2007; Alesso et al., 2012). There appears to be a paucity of reported information about the spatial distribution of soil compaction within CTF systems. This knowledge is required to advance the understanding of crop performance and root behaviour at locations near-permanent traffic lanes, and to quantify impacts on crop yield and quality at the field-scale. In well-designed, fully matched CTF systems with 3-m centres and 12.2-m (40-ft) modules or greater, the traffic footprint is fairly

small, and may represent 15% or less of the field cropped area (Antille et al., 2019). Therefore, compaction at locations laterally outboard of the permanent traffic lanes affects a relatively small number of crop rows. For other CTF systems, in which track gauge widths are not fully matched, the traffic footprint is greater (typically, $\geq$ 15% of the field cropped area). This occurs in CTF systems with unmodified machinery and also when narrower modules are used (e.g., 6-m or 8-m wide, Galambošová et al., 2017). Consequently, the number of crop rows affected by compaction in these latter systems is higher and will depend upon the specific design of the CTF system. This can increase the spatial variability in crop yield and quality, as shown by Jensen et al. (2000).

The objective of this study was to apply geostatistical techniques to analyse cone index data collected from transects perpendicular to the direction of tramlines, which were established to capture the spatial variability in soil mechanical strength in wheeled and non-wheeled soil. Tramlines were created to represent recently established and older CTF systems by controlling the number of passes with a medium-sized tractor. It was hypothesised that the spatial structure of soil penetration resistance and the soil profile area affected by compaction (cone index greater than 2 MPa) would be significantly affected the number of tractor passes.

MATERIALS AND METHODS

The study was conducted in a commercial farm located in Aurelia, Argentina (31°29'8.50" S, 61°27'25.88" W). The area is characterised by a flat relief with deep and moderately well-drained, silty-clay loam soils originated from loess sediments. These soils have relatively high susceptibility to soil structural damage due compaction when moist (Imhoff et al., 2016). The soil at the experimental site was a *Typic Argiudoll* Rafaela Series with the following granulometric composition in the top 0–20 cm: 20 g kg^{-1} (sand), 720 g kg^{-1} (silt), and 260 g kg^{-1} (clay), respectively (INTA, 1991). The site selected for the study had 30 ha and had been under conventional tillage for more than 50 years, but it has been managed under zero-tillage (ZT) in the five years prior to the experiment using a continuous wheat-soybean-wheat crop sequence. In spring 2014, an area of 40×80-m was tilled to remove historical compaction, as shown by Godwin et al. (2015), using a chisel plough fitted with 11-curved shanks, which were mounted on the frame of the implement at regular intervals of 35-cm. The implement was operated at 20 cm deep and at a forward speed of 7 km h^{-1}. Thirty days after this operation was performed, controlled traffic conditions were imposed by applying soil compaction treatments to experimental plots (dimensions: 40×6-m) using a completely randomised block design with three replications ($n = 3$). The experimental treatments represented permanent crop bed (zero-traffic) and permanent traffic lanes of a CTF system, which had 6, 12, and 18 passes of a tractor, respectively. Traffic treatments were completed in two stages, which were spaced seven days apart, and comprised 4+2, 8+4, and 12+6 passes, respectively. The tractor used at the site was a Pauny 120 HP with an overall mass of 6.3 Mg equipped with single, radial tyres (front axle: 14.9×26, rear axle: 23.1×30) inflated to the manufacturer's recommended inflation pressure for load and speed. Average soil water content at the time of traffic was 0.28 g g^{-1}, which was slightly higher than that (0.25 g g^{-1}) required for the Proctor density (1.42 g cm^{-3}).

Soil penetration resistance was measured within each plot to determine the effect of traffic intensity (number of passes) on soil compaction. For this, penetration resistance

readings were taken from 110-cm transects perpendicular to the tramline's direction, and at random locations along the tramline (Fig. 1).
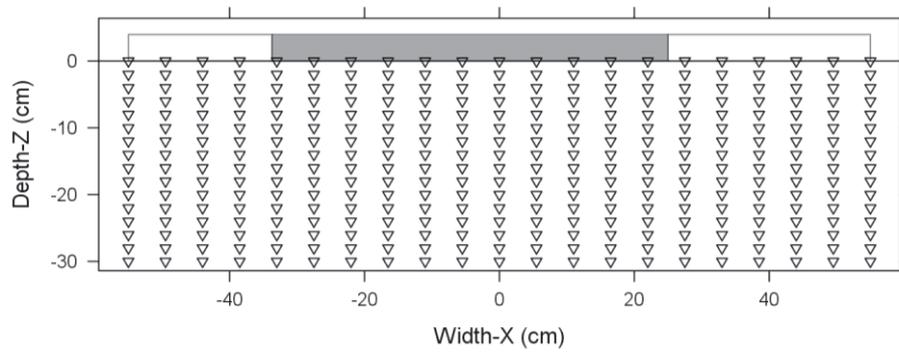
Figure 1. Grid indicating the soil sampling scheme. Inverted triangles denote points where soil penetration resistance measurements were taken. Soil penetration resistance was recorded on transects perpendicular to tramlines with points spaced at 5.5 cm in the *X*-direction, and to a depth of 30 cm at 2 cm depth intervals. The measured area across the tramline is represented by the rectangles on the top of the graph, which show wheeled (darker gray) and non-wheeled zones (lighter gray), respectively.

Measurements were taken on either side of the rut's centreline at regular intervals of 5.5 cm (horizontal direction, *X*-coordinate) and at 2 cm depth increments to a depth of 30 cm (vertical direction, *Z*-coordinate), and the force was digitally recorded using a soil compaction meter (PNT-2000®). Since the centreline of the rut matched the centre of the 110-cm transect ($X = 0$), readings included a wheeled (W) zone of ≈60 cm and two non-wheeled (NW) zones of ≈20 cm and 30 cm either side of the centreline, respectively. The cone had 125 mm^2 base area and 30° apex, and measurements were taken based on ASABE (2019). The 2D grid at each sampling location consisted of 336 observations. Soil water content was determined gravimetrically by taking soil cores at 10 cm depth increments in the 0–30 cm depth range. Cores were taken from both trafficked and non-trafficked soil, respectively. Exploratory spatial data analysis of soil penetration resistance readings was conducted to identify outliers and check for assumptions of geostatistical techniques. Due to skewness (lack of symmetry), data were transformed based on the approach of Webster & Oliver (2007). The non-stationarity of the process was modelled by polynomial functions using spatial coordinates (*X* and *Z*, respectively) as explanatory variables. Estimation of trend coefficients was performed by applying the generalised least squares (GLS) method. The spatial structure of penetration resistance's residuals was examined by computing 2D omnidirectional sample variograms. Box plot diagrams were used to identify outliers (Figure 2). Given outliers were present in the dataset, the Cressie's robust semi-variance estimator (Cressie, 1993) was used to compute the variograms, as shown in Eq. (1).

$$\gamma(h) = \frac{\left[\frac{1}{N(h)} \sum Z(S_i) Z(S_i + h)^{1/2}\right]^4}{0.914 + 0.988[N(h)]^{-1}} \tag{1}$$

where $\gamma(h)$ is the semivariance estimator, $N(h)$ is the number of pairs of observations separated by the vector h, $Z(S_i)$ and $Z(S_i + h)$ are the observations at S_i and $S_i + h$ locations, respectively.

Isotropic exponential, spherical and Gaussian models were fitted to sample variograms and cross-validated by 30-fold cross-validation procedure. The models were selected based on the sum square error and the following diagnostic criteria: correlation coefficient (r) between observed and predicted values, the root mean squared error (RMSE), and the mean squared deviation ratio (MSDR) (Webster & Oliver, 2007). The selected model was used to obtain surfaces of penetration resistance on the X-Z plane by block-kriging on a 1×2.5-cm of the grid. Finally, to synthesise the effect of controlled traffic on soil compaction, the proportion of grid cells with cone index > 2 MPa on each X-Z plane was accounted for and used as a response variable for ANOVA. The data was modeled using a split-plot design with number of passes applied to the main plot following a completely randomized block design, and zones as sub-plots. The blocks were regarded as the random term. Data management and geostatistical analyses were undertaken using the statistical programming language R (R Development Core Team, 2014), and the gstat (Pebesma, 2004) and nlme (Pinheiro et al., 2013) packages.

RESULTS AND DISCUSSION

Median values of soil penetration resistance profiles (depth range: 0–30 cm) corresponding to the traffic treatments are shown in Fig. 2. Untrafficked soil between-traffic lanes exhibited higher soil penetration resistance compared to control soil (0 passes or crop bed). Median values of soil penetration resistance at this location were below the suggested threshold of 2 MPa, but with some exceptions at depths greater than 10 cm. Table 1 shows soil water content recorded in the plots in both wheeled (W) and non-wheeled (NW) zones. Corrections of soil penetration resistance readings for soil water content (Ayers & Perumpral, 1982; ASABE, 2019) were not required given that soil water values were within about 5% difference in all three depths. There were no differences in soil water contents between W and NW zones ($P = 0.15$), which was observed in all measured depths (P-values between 0.25 and 0.96).

Geostatistical analyses of soil penetration resistance data for all 12 plots consistently showed non-stationarity in the mean. With the exception of the 12 passes treatment in Block 1, quadratic functions on both coordinates accounted for the trend and explained between 67% and 88% of the variation in soil penetration resistance (Table 2). The trend on Z could be better explained by the natural increase in soil penetration resistance with increasing soil depth, possibly due to densification of the soil profile and increased clay content (Bt horizon). The trend on X is explained by the effect of tractor passes, which shows significant differences between wheeled and non-wheeled soil, respectively. Readings recorded at the centreline of the rut were consistently higher compared with those at locations laterally outboard of the wheeling or in non-wheeled soil, which was therefore consistent with previous studies (e.g., Way et al., 2009; Antille et al., 2013). Such response is explained by the soil stress distribution at depth and the soil-tyre contact pressure (Misiewicz et al., 2015).
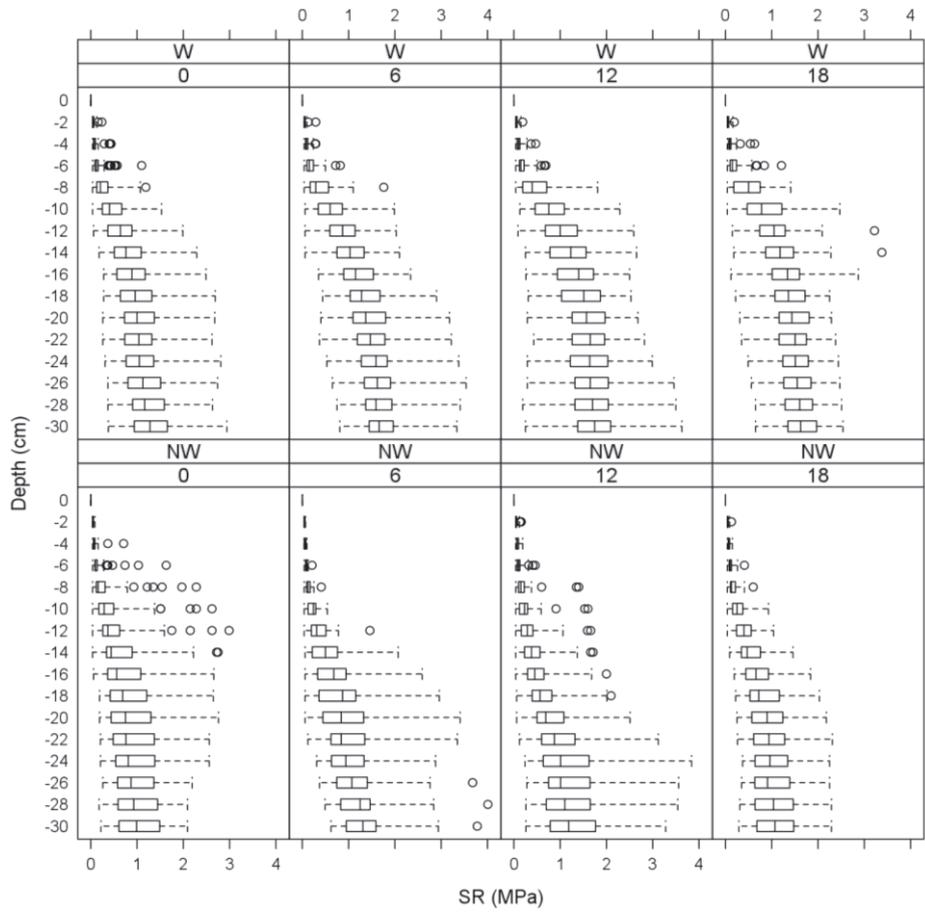
Figure 2. Box plots (Min, Q_1, Med, Q_3, Max, Outliers) showing the distribution of soil penetration resistance (SR) readings for each traffic treatment (0, 6, 12, 18 passes of a tractor) in both wheeled (W) and non-wheeled (NW) zones, respectively. Sample medians of penetration resistance from each depth show the trend of this measurement as a function of depth.

Table 1. Mean soil moisture content (±SD) at the three measured depths in wheeled (W) and non-wheeled (NW) zones in each of the traffic treatments, respectively

| Treatment		Soil depth		
No. of passes	Zone	0–10 cm	10–20 cm	20–30 cm
0	Wheeled	0.28 ± 0.005	0.27 ± 0.010	0.27 ± 0.014
0	Non-wheeled	0.29 ± 0.033	0.28 ± 0.006	0.27 ± 0.012
6	Wheeled	0.27 ± 0.003	0.27 ± 0.016	0.27 ± 0.017
6	Non-wheeled	0.28 ± 0.034	0.27 ± 0.011	0.28 ± 0.011
12	Wheeled	0.26 ± 0.024	0.28 ± 0.017	0.27 ± 0.016
12	Non-wheeled	0.27 ± 0.032	0.28 ± 0.013	0.27 ± 0.017
18	Wheeled	0.26 ± 0.002	0.28 ± 0.007	0.27 ± 0.005
18	Non-wheeled	0.26 ± 0.010	0.27 ± 0.020	0.28 ± 0.025

Residuals obtained after applying the GLS procedure exhibited a structure depicted by the spherical isotropic models presented in Table 2. Fitted ranges varied between 10 and 18 cm, and no differences were detected between traffic treatments ($P = 0.17$). Due to the configuration of the sampling grid (5.5×2-cm), the analysis of directional variograms revealed that the spatial continuity was mainly attributed to the spatial structure in the vertical direction, whereas in the horizontal direction, the spatial structure could be under the minimum lag distance. Despite this, the models shown in Table 2 were fitted assuming isotropy for soil penetration resistance data. Cross-validation of results shows that, even if the process was regarded as isotropic, reasonable good predictions of penetration resistance could be obtained from non-sampled locations.

Table 2. Parameters and 30-fold cross-validation results for the spatial models of soil resistance fitted for each traffic treatment and block

Treatment	Block	Transf.	Trend model Z	X	R^2_{adj}	Variogram Model	Nugget	Sill	Range (cm)	r	RMSE	MSDR
0 passes	1	none	Q	Q	0.68	Sph	0	0.169	15.1	0.98	0.143	0.57
	2	sqrt	Q	Q	0.80	Sph	0	0.032	12.8	0.98	0.113	1.48
	3	sqrt	Q	none	0.70	Sph	0	0.067	17.9	0.98	0.138	1.62
6 passes	1	none	Q	Q	0.78	Sph	0	0.084	13.6	0.98	0.096	0.44
	2	none	Q	Q	0.79	Sph	0	0.226	13.3	0.99	0.149	0.40
	3	sqrt	Q	Q	0.89	Sph	0	0.021	11.3	0.99	0.077	1.00
12 passes	1	sqrt	Q	C	0.78	Sph	0	0.071	13.9	0.98	0.176	1.95
	2	none	Q	Q	0.77	Gau	0.015	0.164	11.7*	0.97	0.146	0.85
	3	sqrt	Q	Q	0.86	Sph	0	0.025	10.7	0.98	0.093	1.15
18 passes	1	none	Q	Q	0.79	Sph	0	0.107	13.7	0.99	0.106	0.45
	2	sqrt	Q	Q	0.78	Sph	0	0.060	18.4	0.99	0.108	1.11
	3	none	Q	Q	0.81	Sph	0	0.105	15.3	0.99	0.094	0.40

*Effective range; Trend model: Q = quadratic; C = cubic; Model: Sph = Spherical; Gau = Gaussian; sqrt = squared root-transformed, respectively. RMSE is root mean squared error, and MSDR is mean squared deviation ratio.

The spatial distribution of soil penetration resistance observed in each plot is shown in Fig. 3. The proportion of grid cells with cone index > 2 MPa showed non-significant interaction ($P = 0.28$) and non-significant main effect of treatments ($P = 0.57$) or zones ($P = 0.36$), which was due to high variability of this measure ($CV \geq 0.65$), also shown by Alesso et al. (2017, 2018). Over a total of 1395 grid cells, the estimated overall mean proportion of grid cells (± 95% confidence interval) with cone index > 2 MPa was 4.9 ± 4.5%. Several studies (e.g., Botta et al., 2019; Horn et al., 2003) have shown that soil compaction increases with increased traffic intensity because of progressively greater soil displacement beneath the tyres (Ansorge & Godwin, 2007). However, in our study, a relatively low compaction was observed within tramlines, even with 18 passes, suggesting that true replication of CTF conditions were not achieved, possibly due to the moderately light-mass tractor used to establish the tramlines.
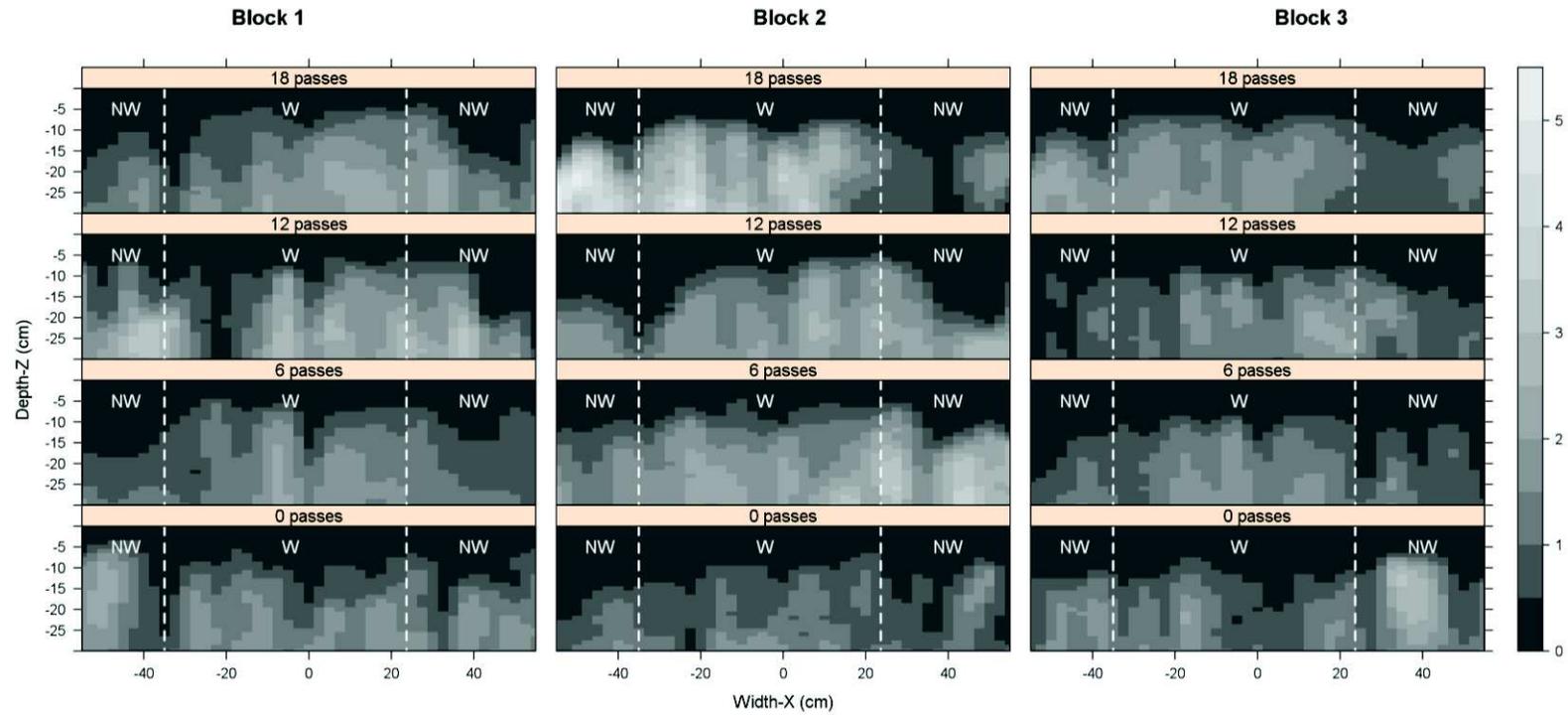
Figure 3. Spatial distribution of soil penetration resistance in vertical planes obtained by block-kriging over sample grids of 110 cm (width-*X*) by 30 cm (depth-*Z*) perpendicular to the direction of established tramlines in each traffic treatment (0, 6, 12 and 18) and block (1–3) in wheeled (W) and non-wheeled (NW) zones, respectively. The grey colour-scale represents levels of soil penetration resistance (MPa).

CONCLUSIONS

The main results derived from this work are summarised below:

- Modelled data showed a significant trend and spatial structure of soil penetration resistance in the vertical plane. Variation in soil penetration resistance with depth explained between 67% and 88% of the variation,
- Residuals were autocorrelated with ranges between 10 and 18 cm. However, the hypotheses formulated prior to this study, could not be verified because the number of tractor passes showed no significant effects ($P > 0.05$) either on the range of spatial dependence of generalised least squares (GLS) residuals or the proportion of grid cells with cone index > 2 MPa,
- The overall mean proportion of grid cells (±95% confidence interval) with values of cone index > 2 MPa ($4.9 \pm 4.5\%$) reflects relatively high variability of this measure, and therefore does not appear to be a reliable parameter to inform future experimental designs.

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