Predicting soil physical properties from morphology

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Abstract
Morphological descriptors of ped size and tightness of *in situ* packing have been developed in New Zealand to predict hydraulic conductivity. These descriptors, together with clay content, were used to define five functional subsoil horizons for eight soil series on the Canterbury Plains and were found to be useful predictors of a number of soil physical properties. In this paper, the same functional horizons (based on two classes of clay content, two classes of ped size and six classes of *in situ* packing) are applied to a New Zealand-wide dataset encompassing a wide range of soil groups. Encouraging relationships were found between functional horizons and bulk density, macroporosity, readily available water, K_s and K_{-40}, but not with total available water, field capacity or wilting point. Relationships between functional horizons and soil physical properties were weakened when standard soil consistence attributes were used in the place of *in situ* packing.

Key words
Functional horizons, hydraulic conductivity, water release characteristics, New Zealand, analysis of variance

Introduction
Soil water retention and hydraulic conductivity data need to be obtained before simulation models can be effectively applied to much of New Zealand. Pedotransfer functions have been developed to estimate soil physical properties from common soil analyses such as carbon, bulk density and soil texture. Application of these pedotransfer functions is particularly valuable for filling gaps in databases that contain the primary soil data variables. However, application of these pedotransfer functions is limited by the small number of points in the landscape with basic soil data available. The greatest amount of information on soil properties and soil variability is contained in descriptions of soil morphology, recorded as part of the process of soil surveys. Pedotransfer functions based on soil morphology therefore have the potential of linking soil physical properties to the wealth of soil horizon descriptions for many points in the landscape.

In the 1980s, Griffiths (1985) developed methods to relate soil morphology to hydraulic conductivity. He found that traditional morphological characteristics were poorly related to hydraulic conductivity. With Peter Singleton, he developed a simple instrument to measure degree of packing of soil *in situ*. This measurement, together with ped size classes, enabled encouraging prediction of K_s and K_{-40} (Griffiths *et al.* 1999). They found 'a combination of low packing and fine peds with rough surfaces was indicative of rapid conductivity, while one of high packing, coarse peds with smooth faces was indicative of slow conductivity'. Webb (2003) investigated the relationship between morphology and soil water retention and hydraulic conductivity data for eight soils series within two drainage sequences on the post-glacial and glacial surfaces of the Canterbury Plains. Pedological horizons were grouped into functional horizons on the basis of soil morphologic attributes expected to have closest relationships with soil physical properties (ped size, ped type, packing class, consistence and presence of argillic horizons). These morphological descriptors were used individually, and in combination, to create sets of functional horizons. These were then tested to identify the morphological descriptors that were most effective for predicting soil water release characteristics and hydraulic conductivity. Horizons with high clay content (clay >35%) needed to be separated because of the correlation of clay content with some soil physical properties. Functional horizons based on a combination of ped size and packing provided the best relationships with a number of soil water retention and hydraulic conductivity data.

In this paper the functional horizons developed in Canterbury are applied to a New Zealand-wide dataset to see if the same relationships hold.

Methods

Soil types

Data used in this paper were derived from soil investigations made for SWAMP (the Soil Water Assessment and Measurement Programme) undertaken between 1984 and 1989. The investigation encompassed key agricultural soils in six regions of New Zealand (Otago, Canterbury, Marlborough, Manawatu, Wanganui and Waikato). The dataset used here consisted of 97 horizons from 41 profiles and encompasses soils from 7 Soil Orders and 18 Groups in the New Zealand soil classification (Hewitt 1998).

Morphology

Comprehensive details of the methods of field description are given in Griffiths *et al.* (1999). Soil structure was described by taking a block of soil of about 0.40 m^2 on the horizontal section. The block is dropped from a standard height for a standard number of drops. The structure units are then gently sieved to separate into appropriate size classes. Each size group is then weighed and recorded as a percentage of the total weight of the block. Degree of packing was measured by a single-vane shear test using the Singleton Blade (Milne *et al.* 1995). The blade is pushed into the vertical face of a soil horizon; the force required to break away the soil from the horizon using the blade is then measured by pushing the blade sideways with a penetrometer. Ten readings were taken from each horizon. When soil conditions were too dry (water tension >50 kPa), shear vane readings were not taken.

Laboratory analysis

Samples were analysed for a range of soil water release characteristics, measured on 55-mm-diameter cores according to the methods of N. Z. Soil Bureau (1972). The list of soil water release characteristics investigated includes macroporosity (the percentage of pores between total porosity and a tension of –5 kPa), field capacity (the volumetric water content at –10 kPa), total available water (the volumetric water content between –10 kPa and –1500 kPa), and readily available water (the volumetric water content between –10 kPa and –100 kPa).

Hydraulic conductivity was measured on 0.10-m-diameter cores (four replicates per horizon). Saturated hydraulic conductivity (K_s) was measured using constant head mariotte devices (10-mm head) and near-saturated hydraulic conductivity was measured at 40 mm water tension (K_{-40}) using modified disc permeameters (Clothier and White 1981). Measurements of K_{-40} and K_s were halted when conductivity was less than 0.004 mm/h.

Data analysis

All horizons were treated as independent entities and grouped into functional horizons based on clay content, ped size, degree of packing and consistence, according to the classes used by Webb (2003) (Table 1). Analysis of variance was used to investigate the similarities and differences between soil properties for different functional horizons. Hydraulic conductivity data were log-transformed to achieve a normal distribution.

Results

Table 2 shows the range of pedological horizons associated with functional horizons based on 'ped size and packing class' and high clay content. Functional horizon definitions cut across pedological horizons resulting in Bg horizons occurring in all five functional horizons, Cg occurring in four, and BA, Bw, and C horizons occurring in three functional horizons.

Table 1. Identification of functional horizons for subsoils. Horizons with > 35% clay are excluded.

Functional horizons	Number of samples	Ped size (mm)	Packing (penetrometer units)
Functional horizons based on ped size and packing			
1	22	<40	<20
2	24	<40	20 - 30
		>40	15 - 25
3	19	<40	>30
		>40	25 - 35
4	15	>40	>35
Functional horizons based on ped size and consistence			
1	21	<40	<firm
2	9	>40	<firm
3	16	<40	firm
4	38	>40	firm
		any	very firm

Table 2. Lists of pedological horizons within functional horizons

Functional horizons	Pedological horizons	Number of horizons
1	BA, Bw, Bg, BC, Cg, C	22
2	BA, Bw, Bg, BC, Cg, C, Eg	24
3	BAg, Bw(g), Bg, Cg	19
4	Bw, Bw(g), Bg, Bgx, Bt, BCg	15
cy	BA, Bw, Bg, Bgt, Bt, C, Cg	20

As found in a previous study (Webb 2003), soils with high clay content (>35% clay) were found to form outliers in the data. So horizons with high clay content (>35% clay) were put into a separate functional horizon and labeled ‘cy’. ANOVA was used to test for differences between functional horizons for a range of soil physical properties. Three sets of functional horizons were tested for difference: four functional horizons based on ped size and packing, then between each of these functional horizons and horizons based on high clay content, and finally four functional horizons based on ped size and consistence.

The four functional horizons based on ped size and packing class formed consistent trends for all properties except field capacity (Figure 1). Five functional horizon comparisons were significantly different for K_{-40}, four for readily available water, and three for bulk density, macroporosity, and K_s (Table 3). The results from this work were compared with the previous results from Canterbury and shown in parenthesis in Table 3. The results are similar with the New Zealand-wide data having 18 comparisons that were significantly different compared with 22 for Canterbury. This shows that the functional horizons developed for a limited dataset retained functional relationships with a much wider dataset.

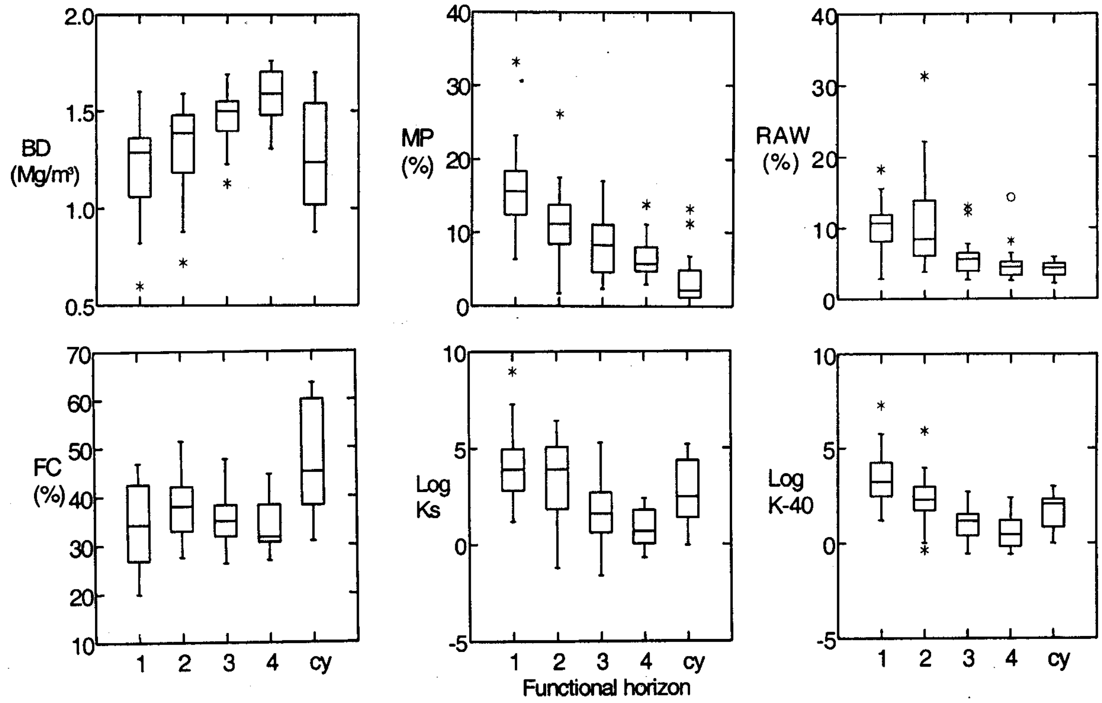

Figure 1. Statistical box-plots for six soil properties. The three lines in the box show medians and upper and lower quartiles. Whiskers show values within 1.5 times the quartile spread, values outside this range are shown as asterisks (Systat 1996). BD, bulk density; MP, macroporosity; RAW, readily available water; FC, field capacity; K_s saturated hydraulic conductivity; K_{40} near-saturated hydraulic conductivity.

Table 3. Comparisons of soil properties for functional horizons based on ped size and packing. Canterbury dataset results are shown in parenthesis when results differ. FC, field capacity; BD, bulk density, MP, macroporosity; TAW, total available water; RAW, readily available water; K_s saturated hydraulic conductivity; K_{-40} near-saturated hydraulic conductivity; Level of significance: * *P*≤0.001, ** *P*≤0.01, * *P*≤0.05, ns = not significant.**

Functional horizon comparisons	Soil water release					Hydraulic conductivity	
	FC	BD	MP	TAW	RAW	K_s	K_{-40}
1-2	ns	ns (***)	** (ns)	ns	ns	ns	*
1-3	ns	** (***)	***	ns	** (*)	**	***
1-4	ns	***	***	ns (**)	** (***)	***	***
2-3	ns	ns	ns	ns	** (ns)	ns	* (ns)
2-4	ns	** (***)	ns (***)	ns (**)	***	** (*)	***
3-4	ns	ns (*)	ns (***)	ns	ns (***)	ns	ns

Table 4 presents the results of comparing soil properties for the four functional horizons, based on ped size and packing class with horizons based on high clay content. Significant differences were found mainly for wilting point (not shown), field capacity, and macroporosity. Wilting point was strongly correlated with clay content (R=0.86) and field capacity was moderately correlated with clay content (R=0.73). No differences were found for total available water and saturated hydraulic conductivity and few differences were found for bulk density, readily available water and K_{-40}.

Table 4. Comparisons of soil properties for functional horizons based on ped size and packing with functional horizons with > 35% clay (cy). Canterbury dataset results are shown in parenthesis when results differ. FC, field capacity; BD, bulk density, MP, macroporosity; TAW, total available water; RAW, readily available water; K_s saturated hydraulic conductivity; K_{-40} near-saturated hydraulic conductivity; Level of significance: *** $P \leq 0.001$, ** $P \leq 0.01$, * $P \leq 0.05$, ns = not significant.

Functional horizon comparisons	Soil water release					Hydraulic conductivity	
	FC	BD	MP	TAW	RAW	K_s	K_{-40}
1 - cy	***	ns	***	ns	***	ns	***
2 - cy	***	ns (**)	***	ns	***	ns	ns
3 - cy	***	ns (***)	* (***)	ns	ns (***)	ns	ns
4 - cy	***	**	ns	ns	ns	ns	ns

Table 5 records the mean and standard deviation values of each soil property for functional horizons.

Table 5. Mean and standard deviation values of soil properties for functional horizons based on ped size and packing and for functional horizon with > 35% clay (cy). FC, field capacity; BD, bulk density, MP, macroporosity; TAW, total available water; RAW, readily available water; K_s saturated hydraulic conductivity; K_{-40} near-saturated hydraulic conductivity.

Functional horizons	Soil water release					Hydraulic conductivity	
	FC	BD	MP	TAW	RAW	K_s	K_{-40}
1	34 (8)	1.20 (0.26)	16.0 (6)	17.7 (5.1)	10.3 (3.7)	585 (1860)	129 (336)
2	38 (6)	1.32 (0.21)	10.8 (5.2)	19.6 (6.4)	10.7 (6.7)	109 (151)	29 (75)
3	35 (5)	1.46 (0.14)	8.4 (4.2)	16.0 (6.0)	5.9 (2.7)	27 (59)	4.0 (3.6)
4	34 (6)	1.57 (0.14)	6.8 (2.9)	15.5 (6.3)	5.1 (2.9)	4 (4)	2.9 (3.1)
cy	48 (12)	1.28 (0.28)	3.6 (3.5)	12.6 (6.4)	4.2 (1.1)	40 (51)	7.6 (5.7)

Lastly, functional horizons based on ped size and consistence (Table 6) were tested for differences. These functional horizons had weaker soil property relationships and fewer significant differences compared with functional horizons where packing class was used in the place of consistence (Table 3 cf. Table 6). Significant differences were largely confined to comparisons with the functional horizon with weakest consistence. The poorer relationships are not surprising given the more subjective nature of assessment of consistence.

Table 6. Comparisons of soil properties for functional horizons based on ped size and consistence. FC, field capacity; BD, bulk density, MP, macroporosity; TAW, total available water; RAW, readily available water; K_s saturated hydraulic conductivity; K_{-40} near-saturated hydraulic conductivity; Level of significance: *** $P \leq 0.001$, ** $P \leq 0.01$, * $P \leq 0.05$, ns = not significant.

Functional horizon comparisons	Soil water release					Hydraulic conductivity	
	FC	BD	MP	TAW	RAW	K_s	K_{-40}
1 - 2	ns	ns	ns	ns	ns	ns	ns
1 - 3	ns	ns	**	ns	ns	**	ns
1 - 4	ns	*	***	ns	ns	***	*
2 - 3	ns	ns	ns	ns	ns	ns	ns
2 - 4	ns	ns	*	ns	ns	ns	ns
3 - 4	ns	ns	ns	ns	ns	ns	ns

There is a wide population distribution of soil properties within functional horizons and a large overlap in soil property values between the functional horizons, even where differences were found to be significant (Fig. 1). This result is to be expected and is realistic of the real-world situations. The development of realistic ranges for attributes is for soil horizons constitute an appropriate dataset for input into simulation studies where soil property variability needs to be taken into account. Lilburne and Webb (2002) used statistical distributions of soil properties, similar to those found here, in a study of nitrate leaching under cropping using the GLEAMS simulation model. The leaching study showed that, despite the large variability of soil physical properties inherent in the soil units, significant differences in leaching could still be found between soil units.

Landcare Research is continuing to investigate the adoption of functional horizons as a basis for describing soil units so that soil physical properties can be assigned to a wide number of soils that currently lack soil physical properties needed in environmental studies (Lilburne *et al.* this publication).

Conclusions

Functional horizons based on ped size, degree of packing, and clay content may be used to provide partitioning of data for readily available water, K_{-40}, K_s, macroporosity and bulk density for subsoils. Wilting point, field capacity and total available water have poor relationships with the morphological descriptors and will need to be predicted from other attributes. It is encouraging that only four functional horizons could be used to characterise horizons from a large array of soil groups and that the same attribute groupings developed under a smaller dataset could be applied to the New Zealand-wide dataset.

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