

# Characterising and improving the deteriorating trends in soil physical quality under banana

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**Abstract.** Deterioration in soil physical quality under intensive tillage practices is a norm rather than an exception. The objectives of this study were to (i) evaluate total porosity (TP) as an indicator parameter to assess the impact of banana cropping on compaction and infiltration in soils, and (ii) assess the effectiveness of different interrow grass-covers in minimising the deteriorating trends. Depth-incremented TP under banana rows and interrows from 4 sites, corresponding forest sites, and from 3 interrow grass-cover treatments were computed from bulk density measurements. The TP results show the compacted depth ranged from 0.35 to 0.45 m in banana rows and from 0.35 to 1.0 m in the interrows. The TP in 0.10 m depth increments decreased in the order: forest > rows > interrows, and was positively correlated with soil organic C (OC) and negatively with wheel traffic stress (WTS). The multiple regression analysis showed that 77% of the variability in TP was accounted for by clay + silt, OC, and WTS. We show that a threshold compaction index (DI<sub>c</sub>) of 0.81–0.83 can be estimated from TP regardless of the soil type. Depending on the soil type and the cultural practices followed, infiltration decreased from 0.75 mm/s in rainforest to 0.23 mm/s under banana in 1 soil type compared with 2.55 mm/s in forest and 0.85 mm/s under banana in another. After 18 months of interrow grass-covers we found the deterioration in TP was minimum under the indigenous grass-cover but not under the 2 improved species. We conclude the interrow grass-covers were effective in minimising WTS associated compaction and reduction in infiltration.

**Additional keywords:** total porosity, compaction index, wheel traffic stress, infiltration, row vs. interrow, grass-covers.

## Introduction

Minimising and/or reversing the deteriorating trends in soil quality after forest clearing and subsequent use for intensive cropping under different management are important in relation to long-term sustainable use and environmental health. Sediment export from the wet-tropical agricultural catchments of north-eastern Queensland, Australia, has been linked to the deteriorating trends in the health and sustainability of the UN-listed Great Barrier Reef and other aquatic ecosystems (Baker 2003; Brodie *et al.* 2003). Generally, the increased sediment export has been linked to the deteriorating trends in soil physical quality under continuous and intensive conventional cultivation practices employing heavy machineries. The impact of heavy machinery wheel traffic stress (WTS) on soil physical quality is usually referred to as compaction, which may lead to increases in runoff and sediment generation. Although numerous reports are available in the analysis of deteriorating trends (McGarry 1990; Congdon and Herbohn 1993; Bridge and Bell 1994; Bell *et al.* 1997; Blair and Crocker 2000; Talbot *et al.* 2003; Drewry *et al.* 2008), almost no information is available on how to reverse the trends, particularly under banana cropping, which lasts for 4–5 years in 1 crop cycle, in the wet-tropical agricultural catchments, north-eastern Queensland, Australia. Talbot *et al.* (2003) reported that physical and hydrological degradation may

occur rapidly in the wet-tropical rainforest soils, particularly on Ferrosols, which are the major soils under intensive banana production in the Tully and Johnstone River Catchments in the wet tropics.

Though the Ferrosols are generally considered to have stable structure due to high sesquioxide and soil organic C (OC) contents (Isbell 1994), under intensive row-crop production systems, significant decreases in aggregate stability and OC have been reported for these soils (Prove *et al.* 1990; Bridge and Bell 1994; Bell *et al.* 1997, 1999), implying increased risk of sediment generation. The interrows under banana occupy ~30–40% of the cultivated land area and are usually kept weed free. The interrows are thus prone to high erosion risk in the wet-tropical catchments that receive 2000–3000 mm rainfall during 5 consecutive months, frequently receiving >50 mm/day. Further, the interrows are subjected to frequent, heavy machinery wheel traffic for harvesting, weeding, and other cultural operations in this environment. Thus, potential exists for the soils under banana interrows to be compacted and possibly structurally degraded, thereby increasing the potential for reduction in infiltration and consequently high runoff and sediment generation. Several agencies have been encouraging growers to switch to better management practices, such as no-till, that will reduce/minimise sediment export; however, growers are

seeking reliable, low-cost, and low-technology indicators to self-assess the effectiveness of the changed management options.

The responses of soils to changes in management practices can be characterised by indicators which reflect the health status of the soil (Doran *et al.* 1994). Several soil properties have been proposed as indicators and they are grouped broadly into 3 categories: physical, chemical, and biological (Doran *et al.* 1994). For example, soil physical health is characterised by indicators such as bulk density (BD), water retention, conductivity, infiltration, least-limiting water range, soil strength, dispersible clay, and stability and distribution of water-stable aggregates (Arshad and Coen 1992; Bridge and Bell 1994; Bell *et al.* 1997; Zou *et al.* 2000). Each one of these indicators describes a given physical function or a process in soils. Though infiltration provides a measure of the ease with which water enters and redistributes itself in soil profiles, the water-entry process is closely linked to other soil properties such as dispersible clay, aggregate slaking (stability), soil porosity, and pore connectivity. In this context, Gregorich (1996) suggested the need for a single property that possesses the ability to reflect several functions or processes.

An integrated response indicator is preferred because the measurement of several properties is expensive, time-consuming, and difficult to interpret for a given purpose. Dexter (2004) proposed the use of the soil physical parameter,  $S$ , that integrates the impact of porosity, water retention, soil structure, texture, and OC on soil physical health; i.e. it is a holistic soil physical health indicator. However, experimental determination of  $S$  is laborious, time-consuming, and expensive. For these reasons, Dexter (2004) proposed empirical equations to predict  $S$  from BD. However, if one is to use BD to predict  $S$ , then the question arises as to why we cannot use BD instead of  $S$  as an indicator to reflect several physical functions/processes. Further, experimental determination of BD is low-technology and cost-effective and can even be undertaken by growers, in contrast to the other soil physical properties mentioned previously. Though BD has been widely used as a low-technology indicator to characterise compaction, studies relating its ability to reflect the integrated impact of other soil physical processes/functions have not received much attention, particularly for the wet-tropical agricultural soils in Australia.

It should also be noted that several soil physical processes, such as infiltration, soil water redistribution, water retention and conductivity, and soil aeration are more closely associated with total porosity (TP) than BD, though the former are computed from the latter. Thus, we believe that it is physically more relevant to link TP to transport (water and air) processes in soils than to BD. Therefore, in this study we (i) evaluate TP as an indicator parameter to assess the impact of banana cropping on compaction and infiltration, and (ii) assess the effectiveness of different interrow grass-covers in minimising/reversing the deterioration trends.

## Materials and methods

### *Study area and banana cultivation*

In the wet-tropical coastal catchments of Australia, banana production is a major industry covering >10 000 ha. The major soils under intensive banana production in these

catchments are basaltic Ferrosols and alluviums derived from basalts and other source materials (Isbell 1996). Generally, 2 rows of bananas are grown on either side of raised beds, ~300–500 mm high and 1.5–2.0 m wide with ~1700 plants/ha. The banana plants (*Musa cv.* Williams, AAA, Cavendish subgroup) are usually established from 0.5–1.0 kg vegetative corm pieces planted in June–August. Standard cultural practices recommended for banana cultivation are followed (Kernot *et al.* 1998), including mould-board ploughing followed by 2–3 rotary or tine tillages before planting, N and P fertiliser application at planting followed by 8–12 applications of N and K/year (300–450 kg N and 600–700 kg K/ha.year), and frequent pesticide applications for fungal, nematode, and stem borer diseases and weed control. These, plus harvesting and other load-carrying operations, are carried out using heavy 4-wheel tractors even when the soil is relatively wet, suggesting the potential for high wheel-traffic-induced physical stress (WTS) on the soil, generally referred to as compaction. Mini-sprinkler or drip systems are used for irrigation and fertigation during August–December depending on crop demand.

In this study, field investigations in farmers' paddocks were conducted at 4 sites representing different soil types and cultivation practices (Table 1). The Kennedy and Tully sites were in the Murray and Tully River Catchments, respectively, separated by 30 km aerial distance. The other 2 sites were at Mission Beach in the Hull River Catchment on the coastal strip. The Mission Beach sites were ~30 and 50 km (aerial distance) from the Tully and Kennedy sites, respectively. The conventionally cultivated banana block at Mission Beach was ~100 m from the organic block. In the organic block, the wheel-traffic for cultural operation was minimal and there was no application of synthetic fertilisers and agrochemicals. At each site, soil samples were taken from nearby rainforest also to allow paired-site comparisons.

Because the number of sites required for multiple regression analysis was insufficient, we obtained BD data from other researchers in Queensland and we refer to the data as being from non-experimental sites (Tables 1 and 2). The data we obtained from these workers include BD and textural composition of soils and brief cropping history. The data from these sites in conjunction with the experimental sites improved the prediction capability of the multiple regression equations.

In another study located ~0.5 km (aerial) distant from the Tully banana block, an interrow grass-cover experiment was conducted to determine the changes in soil physical health associated with grass-covers. The soil type at this site is a Dermosol. Though the interrow grass-cover experiment had several treatments, we selected only 4: the bare control, pinto peanut (*Arachis pintoi*), carpet grass (*Axonopus affinis*), and the indigenous native grass (*Paspalum conjugatum*). The experimental area was 50 m by 91 m, comprising 4 double rows of bananas on 2 by 2 m spacing and 4 replications for each grass-cover treatment. The grass-cover treatments were randomly arranged in interrows measuring 5 m in width by 12.5 m in length. The experiment was established in January 2004 in a banana paddock that was 2 years old, and standard cultural practices recommended for banana cultivation were also followed in this paddock (Kernot *et al.* 1998). The interrow

**Table 1. Catchments and site characteristics**

Catchment characteristics	Murray River	Tully River	Hull River
Total area (km <sup>2</sup> )	1107	1683	248
Area under cropping (km <sup>2</sup> )	588	589	87
Area under banana (ha)	976	3695	336
Annual rainfall (mm)	2239	4118	2739
<b>Site characteristics</b>	<b>Experimental site/village in the catchments</b>		
Location characteristics	Kennedy site	Tully site	Mission Beach site
Longitude	145°55'2"	145°47'26"	146°5'18"
Latitude	18°12'33"	17°54'51"	17°51'32"
Soil type	Dermosol	Dermosol	Ferrosol
Cropping history	<20 years banana >20–50 years sugarcane >50 years native rainforest	<15 years banana >15–70 years sugarcane >70 years native rainforest	<20 years conventional banana 15–50 years sugarcane >50 years native rainforest <12 years organic banana
<b>Non-experimental sites</b>	<b>Soil type</b>	<b>Cropping history and spacing of the orchards</b>	
Site 1 (northern New South Wales, Clunes)	Ferrosol	Macadamia (cv. HAES), 13–14 years old, 8 by 4 m, bare interrows.	
Site 2 (southern Queensland, Gympie)	Shallow grey sand	Macadamia (cv. HAES), 18 years old, 10 by 7 m, well grassed and mown interrows.	
Site 3 (central Qld, Bundaberg)	Kandosol (red earth)	Macadamia (cv. HAES), 13–14 years old, 8 by 4 m, some bagasse application in interrows.	
Site 4 (north Qld, Tolga)	Ferrosol	Macadamia (cv. HAES), 15 years old, 10 by 5 m, sparse grass-cover in the interrows.	
Site 5 (north Qld, Tolga)	Ferrosol	Macadamia (cv. HAES), 19 years old, 8 by 5 m, interrows with African stargrass, carpet grass, weeds.	

**Table 2. Textural composition, soil organic C, and bulk density in the 0–0.10 m depth used to develop equations in Tables 3 and 4**  
CT, Conventionally filled; Org, organic cultivation

Experimental sites	Clay (%)	Silt (%)	Organic C (mg/kg)	Bulk density (Mg/m <sup>3</sup> )
Kennedy: Row	29	21	225	1.22 ± 0.03
Interrow				1.59 ± 0.04
Forest	20	21	406	0.95 ± 0.03
Tully: Row	25	22	183	1.21 ± 0.03
Interrow				1.52 ± 0.03
Forest	20	17	394	1.15 ± 0.02
Mission Beach (CT): Row	49	27	295	1.05 ± 0.02
Interrow				1.33 ± 0.03
Forest	30	15	415	1.00 ± 0.07
Mission Beach (Org): Row	43	30	376	1.10 ± 0.03
Interrow				1.23 ± 0.06
Forest	30	5	415	1.00 ± 0.07
<b>Non-experimental sites</b>				
Site 1: Row	50	29	470	0.84
Interrow	36	30	710	0.81
Forest	46	34	750	0.62
Site 2: Row	9	11	250	1.39
Interrow	7	10	330	1.43
Forest	9	11	250	1.22
Site 3: Row	17	14	140	1.49
Interrow	15	15	250	1.47
Forest	10	10	180	1.33
Site 4: Row	57	22	210	0.96
Interrow	55	23	230	1.19
Forest	30	40	103	0.79
Site 5: Row	56	23	220	1.07
Interrow	53	24	300	1.25
Forest	62	20	330	1.11

grass-covers were seeded on 9 January 2004 and were kept free from other weeds/vegetation. Soil sampling for BD was conducted during mid June 2005, i.e. ~18 months after the establishment of grass-cover treatments.

#### Total porosity

From each site, 1.0 m long triplicate soil cores (44 mm in diameter) were taken from a given row and from the adjacent interrow using a hydraulic rig. The procedure was repeated in the nearby rainforest (where there were no rows or interrows), which was usually not more than 50 m distant from the corresponding banana block. Each one of the 1.0 m cores was segmented at 0.10 m length increments for BD determination. Using the same rig, soil cores with 0.10 m depth increments up to 0.40 m depth were taken from the grass-cover experiment. The field-moist cores were weighed in the laboratory, oven-dried at 105°C for 24–36 h, and weighed again to determine oven-dry soil mass. The BD was computed using oven-dry soil mass and soil volume. Using the BD data, the total porosity (TP) for each 0.10 m depth increment was computed using the following equation:

$$TP = 1 - BD/2.65 \quad (1)$$

where 2.65 Mg/m<sup>3</sup> is the absolute particle density of soils.

#### Compaction index

Reichert *et al.* (2009) proposed a concept to quantify the degree of compaction by dividing BD of cultivated soil by a reference BD value for the same soil determined at different water potential in the laboratory. In this study we modify this

concept using the forest or undisturbed soil BD as reference and define the degree of compaction by an index (DI) as a fraction obtained by dividing the TP of cultivated soil by that of the corresponding forest soil. The advantage in our approach is that DI directly reflects losses in TP relative to the reference and can be used to quantify the degree of compaction or losses in TP in a given soil as affected by different management/tillage practices.

#### Particle size distributions

Using a hand-pushed metallic corer (44 mm in diameter), 4 cores, 0–0.10 m depth, were taken from a given banana row from each site and the procedure was repeated in the nearby forest. The cores were taken 1–2 m away from where the BD cores were taken. The cores were air-dried in the laboratory to constant moisture content and a subsample from each core was ground and passed through a 2-mm sieve; the material <2 mm was used for laboratory analysis. The particle size distribution (PSD) analysis on each ground sample (<2 mm) was conducted using the procedure described by Gee and Bauder (1986). The hydrometer and pipette methods are sedimentation procedures that are accepted as standard methods of particle-size analysis. A second ground subsample (<0.5 mm) from each core was used for total organic C determination by combustion using a Leco C-N analyser. The mean PSD and OC values for each site are reported in Table 2.

#### Infiltration

Infiltration measurements were conducted using double-ring infiltrometer (Bouwer 1986) in the rows ~2–3 m from where the samples for BD measurements were taken and similarly under forest. The inner ring height and internal diameter were 0.20 m and 0.30 m, respectively. The height and diameter of the outer ring were 0.30 m and 0.75 m, respectively. First, the outer ring was pushed at least 0.05 m into the soil, and thereafter 2 inner rings were pushed in a similar fashion inside the outer ring such that they were equally spaced within the outer ring. The soil surface within the rings was hand-levelled, and any stones, debris, leaves, and sticks were hand-removed. The outer ring was filled with water to a depth of ~0.20 m, and immediately following this, the 2 inner rings were filled with water to a depth of 0.15 m. The time taken for every 10 mm drop in height in the inner rings was recorded until ~0.12 m of water had infiltrated into the soil. The measurements from 4 inner rings under a given row or rainforest sampling location were averaged for statistical curve fitting. The cumulative infiltration (CI) data were fitted to the Kostikov (1932) equation:

$$CI = pt^{-q} \quad (2)$$

where  $t$  is time in seconds and  $p$  and  $q$  are regression constants obtained using nonlinear regression fitting procedures. Equation 2 was developed specifically for infiltration measurements made from time-varying ponded water depths. The time-varying ponded depth condition simulates the reality of gravity irrigation using basin and border systems. Warrick *et al.* (2005) showed that results obtained using a constant head procedure were similar to those obtained using Eqn 2.

#### Statistics

The BD data from the rows, interrows, and rainforest sampling locations were used to compute the mean and standard error (s.e.) for each 0.10 m depth increment. The TP computed using Eqn 1 was also subjected to a similar analysis. The association between any 2 given variables was determined using simple linear regression analysis (SAS 1991).

## Results and discussion

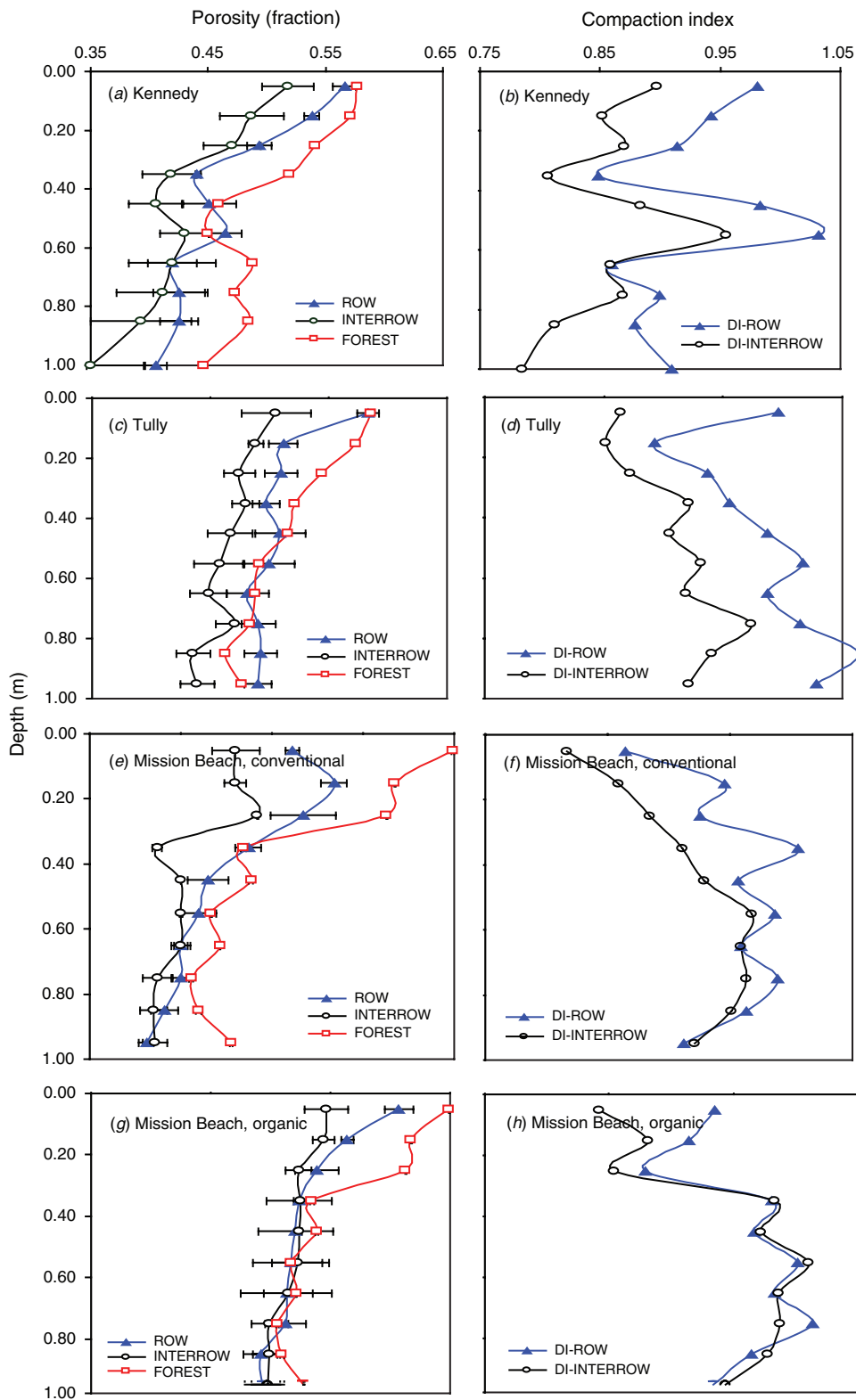
#### Soil properties

A brief description of inherent soil properties that were experimentally determined is provided here as background information to improve the understanding of their impact on compaction and infiltration. The clay content across the 4 experimental sites ranged from 20 to 49%, silt from 15 to 30%, OC from 183 to 415 mg/kg, and BD from 0.95 to 1.59 Mg/m<sup>3</sup> (Table 2). The clay content across cultivated farms was higher than the corresponding forest, particularly in Mission Beach. A similar trend was also observed for silt content, except for the Kennedy site. Higher clay or silt in the farm soils compared with the corresponding forest may be due to the exposure of subsoil through erosion. As anticipated, the OC in the forest soil was higher than the corresponding cultivated soil. At any given site, the forest selected was the only available nearest to the corresponding farm; hence, the difference in clay or silt between them is attributed to spatial variability at distances as low as 30 m (e.g. Tully). Further, in the general soil classification scheme, given the short distance between the farm and the corresponding forest, the soils in both were grouped as the same soil type (Murtha 1986). In general, the BD at a given site was: banana interrow > banana row > forest. The BD in the rows was: Kennedy ≈ Tully > Mission Beach organic > Mission Beach conventionally tilled (Table 2). A similar trend was observed for the interrow BD, except for the conventionally tilled interrow BD at Mission Beach.

The clay content across the 5 non-experimental sites ranged from 7 to 62%, silt from 10 to 40%, OC from 140 to 1030 mg/kg, and BD from 0.62 to 1.49 Mg/m<sup>3</sup>. These data were required by, and used only in, the development of multiple regression equations relating TP as a function of clay + silt, OC, WTS, and the interactions involving these variables. Discrepancies similar to that observed at the experimental sites were also found for clay content between the cultivated and forest soils in this dataset, particularly for sites 1, 3, and 4. We believe there is an advantage in using these data along with the experimental sites, because the increases in the ranges in clay, silt, OC, and BD or TP were anticipated to increase the accuracy in the predicted values of TP.

#### Total porosity

The depth incremented (0.10 m) TP distributions shown in Fig. 1 indicate that it varied within the profile and the variations depended on the site (soil type), row *v.* interrow of banana at a given site, forest *v.* interrows at a given site, and row *v.* forest at a given site. At the Kennedy site, generally the TP was: interrows < rows < forest up to 1 m depth, suggesting WTS induced reductions in TP or compaction at least up to 1 m depth. We did not examine the TP at depths >1.0 m. At the Kennedy



**Fig. 1.** Comparisons of porosity distributions in the rows and interrows of banana with the corresponding nearby forest soil and the compaction index (DI).



site, the TP was greater in the interrows than rows up to 0.75 m depth. Thus, the depth to compaction at this site ranged from 0.75 to 1 m. The reduction in TP in the rows compared with the forest is attributed to the effects of cropping and cultivation practices that occurred after forest clearing. The reduction in TP in the interrows is attributed to the same reasons as for the rows and to other operations such as weeding, harvesting, spraying, and other cultural practices performed only in the interrows using heavy machineries. Thus, the lower TP in the interrows than rows is due to increased WTS in the interrows linked to the farm management practices.

The TP distribution patterns at the Tully and Mission Beach sites are qualitatively similar to those observed at the Kennedy site (Fig. 1), but quantitatively the distributions and the depths to compaction varied with sites and cultivation practices, particularly at the Mission Beach site. The compacted depth in the rows at Tully farm was 0.40 m compared with 0.75 m in the interrows, implying the increases in WTS in the interrows was responsible for the greater depth to compaction, by ~0.35 m. The depth to compaction in the conventionally tilled banana at Mission Beach block extended down to >1 m, compared with 0.40 m in the rows, again implying the increases in WTS extended the depth to compaction by ~0.60 m in the interrows. There was no difference between row and interrow depth to compaction (0.40 m) in the organically farmed plots at Mission Beach, and this indirectly provides support to the claim that higher WTS in the interrows than rows was due to increased wheel traffic.

A comparison of row v. interrow TP distributions for the 3 sites shows the reduction in interrow TP was much higher than in the corresponding row, particularly in the top 0–0.25 m depth. In this context, it should be noted that the rows were on raised beds, up to 0.25–0.30 m height, implying that higher TP in rows compared with interrows may be an artefact of the raised bed condition. Across the sites, the largest reduction in TP was observed under the conventionally tilled banana interrows at Mission Beach and the least depth to compaction in the interrow was found at the same site but under organic farming practices (Fig. 1). This suggests the soil at Mission Beach is very susceptible to WTS-induced compaction compared with the other sites, indicating the need for adoption of reduced wheel traffic management practices at this site.

The simple linear correlation between TP and clay or OC or ST (i.e. the WTS term) indicated the association was significant at  $P=0.05$  for OC and ST, but not for clay (Eqns 1–3 in Table 3). The ST term in the analysis is a qualitative variable but we changed it into a quantitative variable by defining the WTS in forest system as 0 (no wheel traffic stress), rows 1 (moderate stress), and interrows 2 (high stress). The  $r$  values indicated that the association between TP and ST is stronger than that between TP and OC, suggesting an overriding negative impact of ST on TP over OC. Every unit increase in ST reduced the TP by 0.036 units compared with an increase of 0.025 units by OC. It should be noted that a unit increase in OC may occur over a longer time frame than ST.

Though multiple regression, Eqn 5 in Table 3 is significant, the clay + silt term is not significant. Nevertheless, the equation indicates that TP increased with increasing clay + silt and OC contents. Equation 5 also indicates that a unit increase in ST will

**Table 3. Simple linear associations between total porosity (TP) and clay, or organic C (OC) or the wheel traffic associated stress (ST) or OC/(clay + silt) or ST/(clay + silt) or (ST\*OC)**

Only the associations significant at  $P=0.05$  are reported.  $R^2$ , Coefficient of determination;  $r$ , correlation coefficient

Equations for experimental sites	$r$	$P$
1. TP = f(clay + silt)		n.s.
2. TP = 0.49 + 0.025OC	0.60	0.03
3. TP = 0.61 – 0.036ST	0.78	0.01
Multiple regression equations	$R^2$	
4. TP = 0.60 – 0.0093(OC*ST)	0.36	0.05
5. TP = 0.57 + 0.00087(clay + silt) + 0.0013OC – 0.044ST	0.57	0.03
Equations for data pooled across experimental and non-experimental sites		
Linear equations		
6. TP = 0.44 + 0.0023(clay + silt)	0.65	0.01
7. TP = 0.46 + 0.03OC	0.70	0.01
8. TP = 0.62 – 0.047ST	0.45	0.02
Multiple regression equation	$R^2$	
9. TP = 0.43 + 0.0019(clay + silt) + 0.020OC – 0.032ST	0.77	0.01

reduce TP by 0.044 compared with an increase in TP by 0.0013 units for OC, implying the negative impact of ST is much greater than the positive effect of OC. This is supported by Eqn 4 in Table 3, which indicates the interaction involving OC and ST was significant and strong, implying the negative impact of ST on TP might not be overcome by increases in OC. This, we believe, is due to the fact that a unit increase in OC may take several years and may not occur under conventional tillage systems, but on the other hand, an increase in ST by 1 unit is a common occurrence under conventional cultivation practices. We have indicated that the Mission Beach soil was very susceptible to WTS and when this stress was removed in the organic farming system, the susceptibility decreased substantially, implying the negative impact of ST on TP was larger on high clay soils than on low clay. To clarify the non-significance of the clay + silt term in Eqn 5 (Table 3), we obtained data from other researchers in the neighbouring catchments (Table 1, non-experimental sites 1–5) and repeated the multiple regression analysis. The Eqns 6–9 (Table 3) obtained in the analysis, while reconfirming previous the models, produced significantly improved models, as indicated by high  $R^2$  values, and significant coefficients for clay + silt.

The impact of soil PSD and their packing is believed to reflect the pore space arising from packing of the particles and thus considered to be textural porosity (Fies 1992; Bruand and Cousin 1996). It is generally assumed that textural porosity is unlikely to be impacted by WTS or other land management practices (Richard *et al.* 1999). Increases in OC are generally associated with improvements in soil structure, implying increases in structural porosity. Thus, the increases in TP with increasing OC in our study are attributed to an increase in structural porosity. On the other hand, the increases in TP with increasing clay + silt is usually associated with textural porosity (Fies 1992; Bruand and Cousin 1996; Richard *et al.* 1999). Thus, Eqns 5 and 9 (Table 3) indirectly suggest the reductions in TP under cropping are due to decreases in both structural and textural porosities as affected by WTS. Bruand and Cousin

(1996) also indicated that textural porosity increased at the expense of structural porosity under low external pressure or stress applied at low soil water matric potential. However, when the stress increased there were losses in structural porosity without any loss or gain in textural porosity. They also showed that at high soil water matric potentials, although there were losses in structural porosity, these losses were not accompanied by any changes in textural porosity. These 3 scenarios are very common in the studied catchments; therefore, we suggest potential existed for substantial losses in structural porosity and, to limited extent, in textural porosity.

### Compaction index

The compaction index (DI) distributions shown in Fig. 1 indicate that it depended on row *v.* interrows, and the tillage practices followed in a given site and varied between sites. A comparison of TP with the corresponding DI indicates the higher the TP, the larger the DI and *vice versa*, implying smaller DI values are indicative of high compaction. The index was higher for rows than interrows; the average value for DI under the rows at the Kennedy site of 0.93 compared with 0.86 for interrows. Because DI was computed using TP, we suggest the WTS-induced losses in TP, relative to the corresponding forest, was 0.07 in the rows compared with 0.14 for interrows.

Elsewhere, we stated the largest reductions in TP occurred at the Mission Beach site, but the DI values indicate it was at the Kennedy site. The contradictions are explained in terms of the differences in the computational procedures used. Unlike TP, the DI values were normalised in relation to the forest sites; therefore, we suggest the DI values are more appropriate for row *v.* interrow comparison of a given site.

Using the DI values, we proceeded to propose a threshold DI ( $DI_t$ ) to explore whether the threshold  $DI_t$  is similar across soils. For this purpose we hypothesised that a loss in TP of 0.10 is acceptable and this loss will have minimum impact on soil–water processes, root activity and aeration, and consequently on yield. The average TP ( $TP_{av}$ ) for a 1-m profile for each forest site was computed and the  $DI_t$  was estimated as follows:

$$DI_t = (TP_{av} - 0.10) / TP_{av}$$

The estimated  $DI_t$  for the Kennedy site was 0.82 compared with 0.81 for the Tully site and 0.80 for Mission Beach. Similar estimations for the 5 non-experimental sites produced  $DI_t$  values ranging from 0.82 to 0.87. The larger  $DI_t$  for the non-experimental sites is attributed to the following. The  $DI_t$  values for these sites were computed using the  $TP_{av}$  for the top 0.20 m and low forest soils BD ( $1.00 \text{ Mg/m}^3$ ) compared with the experimental sites (Table 2). The mean  $DI_t$  for the non-experimental sites was 0.83 compared with 0.81 for the experimental site. We therefore suggest that  $DI_t$  0.81–0.83 can be used as an index to characterise the critical/threshold limit for WTS-induced compaction. For the data pooled across the experimental and non-experimental sites, the simple linear associations between  $DI_t$  and clay or OC or clay+silt or  $OC \times \text{clay+silt}$  were not significant. However, multiple regression analysis for  $DI_t$  as a function of the above variables produced a significant equation for silt and OC

variables (not shown). These contradictions suggest further research is needed to justify the 0.10 permissible losses in TP as the threshold, and more TP data obtained across cultivated and forest soils types up to 1.0 m depth to verify the dependence of  $DI_t$  on soil properties and interaction terms involving these properties.

### Infiltration

The CI data provided in Fig. 2 indicate the infiltration process has not reached steady-state in any 1 of the 3 profiles either under cropping or in the forest. The reason for not reaching steady-state may be that the initial maximum depth of water in the infiltrometer was insufficient due to ring height limitation. The data indicate the average infiltration under forest ranges from 0.75 mm/s at Kennedy site to 2.33–2.55 mm/s at Tully and Mission Beach sites, suggesting the infiltration in Kennedy site is inherently low (Table 4). Forest clearing and subsequent cropping for several decades have led to 93% less infiltration compared with the corresponding forest at Tully site, 69% at Kennedy site, and 89% at the organic block and 64% under conventional banana at Mission Beach site. We anticipated the average infiltration in the organic block at Mission Beach to be higher than the conventional practice, and we are not in a position to provide any reason for this discrepancy.

As mentioned previously, we suggest the reduction in CI was due to decreases in TP, pore-continuity, pore-connectivity, and/or pore-collapsing and increases in surface sealing. The CI reflects not only the water entry process but also its redistribution in the profile including storage (retention), vertical and lateral spread, and drainage of the infiltrated water. The smallest decrease in TP, 3%, was observed at Tully, yet this brought about the largest reduction in infiltration at this site, where the infiltration under forest was the highest among the 3 sites. This suggests the soil at this site was very sensitive to WTS-induced changes in the soil–water entry, redistribution, and other processes. Although the infiltration under forest at Kennedy is about one-third of that at the other sites, the reduction in infiltration under cropping is least for similar decreases in TP, suggesting the reduction in infiltration depended not only on the decreases in TP, but also on the other pore-related characteristics mentioned above. To explore the impact of these properties on CI, we fitted the CI data to the Kostiakov (1932) vertical infiltration model (see details in the *Materials and methods*) and suggest whether the fitted parameters can be used as surrogates to explain the differences in CI.

The non-linear fitting procedure produced significant equations ( $P < 0.05$ ) with  $R^2$  ranging from 0.64 to 0.99 (Table 4), suggesting the model satisfactorily described the CI process mathematically. Therefore, we propose the coefficient for the slope parameter can be used as a surrogate to characterise the time-dependent water-entry, redistribution (vertical and lateral), changes in profile storage, and drainage processes. In general the  $q$  value for forest soil is greater than the corresponding cultivated soil and across sites it increased in the order: Tully < Mission Beach < Kennedy, except for the conventional banana block at Mission Beach site. We therefore suggest that  $q$  indirectly reflects a degree of the deterioration in pore quality characteristics. Similar trends were not observed for the  $P$  value; thus, we

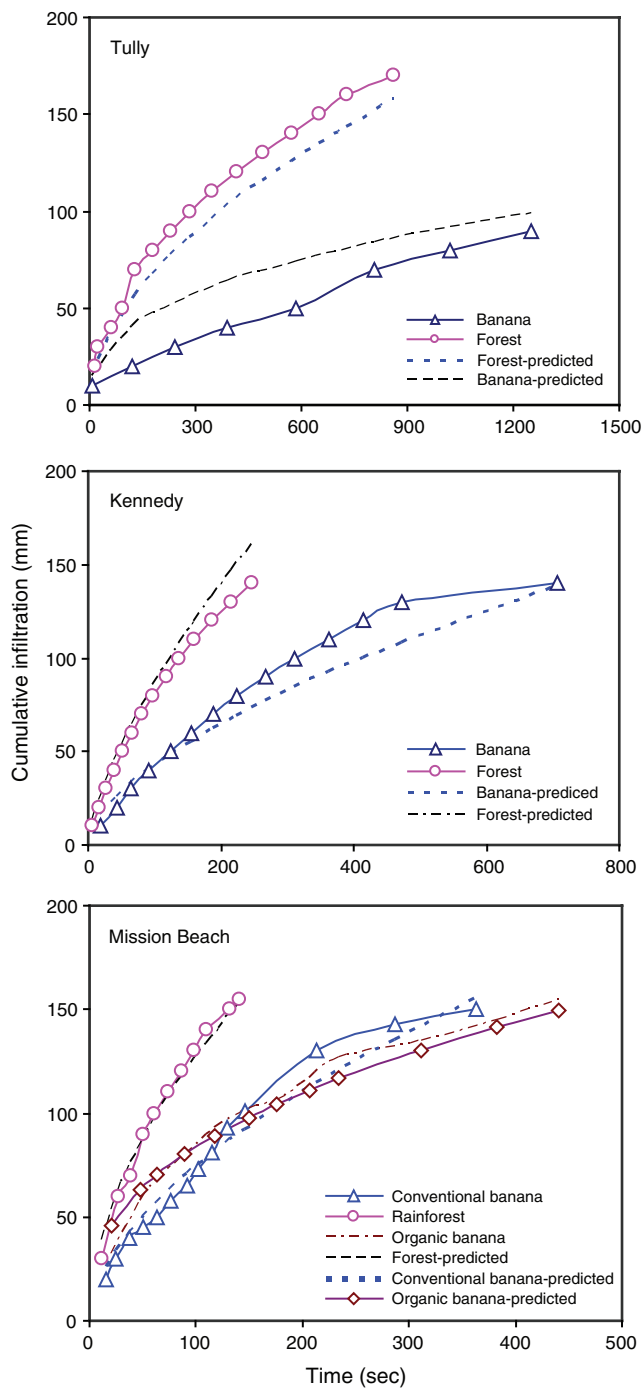


Fig. 2. Comparisons of cumulative infiltration in soil profiles.

suggest the  $p$  parameter is less useful to characterise soil-water processes.

Because, we claimed the  $q$  parameter can be used as a surrogate to characterise the integrated impact of pore characterise on CI, we proceeded to explore its association with primary soil properties. Significant positive associations existed between  $q$  and clay or OC or TP or clay+silt or the interaction term involving OC and clay+silt (Table 4), providing support to our claim. We suggest the clay or clay+silt term reflects the impact

**Table 4.** Estimates for the  $p$  and  $q$  parameters of the Kostikov (1932) cumulative infiltration model ( $CI=pt^q$ ) and simple linear associations between  $q$  parameter and total porosity (TP) or clay or organic C (OC) or (clay+silt) or  $[OC*(clay+silt)]$ . All the associations are significant at  $P<0.05$  and  $r$  is correlation coefficient

CT, Conventional till; Org, organic farm; Av-IR, average infiltration rate;  $R^2$ , coefficient of determination; numbers within parentheses are standard error of estimate

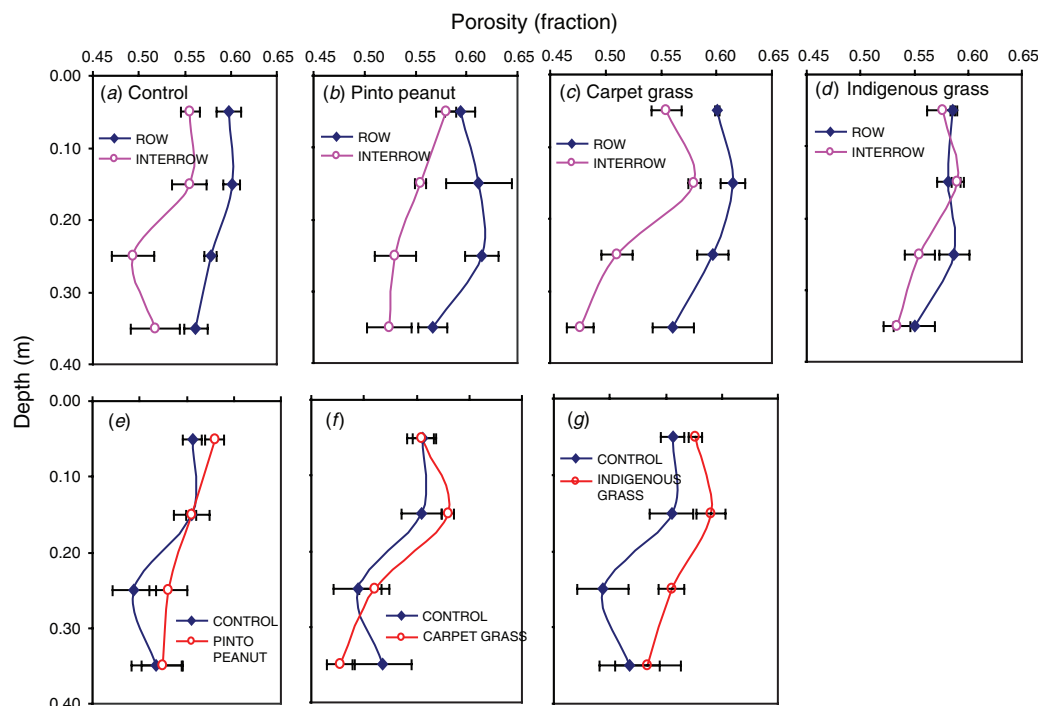
Site	Treatment	Estimates for parameters			
		Av-IR (mm/s)	$p$	$q$	$R^2$
Kennedy	Banana	0.23	0.27 (0.07)	0.60 (0.05)	0.85
	Rainforest	0.75	0.36 (0.05)	0.69 (0.03)	0.99
Tully	Banana	0.18	0.66 (0.37)	0.38 (0.07)	0.64
	Rainforest	2.55	0.41 (0.26)	0.54 (0.10)	0.67
Mission Beach	Banana (CT)	0.85	0.54 (0.15)	0.57 (0.05)	0.78
	Banana (Org)	0.27	1.39 (0.28)	0.39 (0.04)	0.79
	Rainforest	2.33	1.06 (0.20)	0.54 (0.04)	0.89
Linear equations for which intercepts were set to zero					$r$
$q=0.90TP$					0.98
$q=0.015Clay$					0.92
$q=0.15OC$					0.96
$q=0.0092(clay+silt)$					0.93
$q=0.027OC*(clay+silt)$					0.92

of primary soil particles on water-entry and subsequent soil-water processes and we define this as textural impact on soil-water processes as influenced by pore characteristics. On the other hand, the impacts of OC and the interaction involving  $OC*(clay+silt)$  are defined as structural impact. The small differences in  $r$  values for the correlations suggest it is difficult to discriminate the relative importance of the impact of textural v. structural properties of soils on pore characteristics and consequently on soil-water processes.

Stange and Horn (2005) indicated that porosity and pore-geometry control unsaturated hydraulic properties such as water entry, retention, and hydraulic conductivity. It is worth noting that Assouline (2006) showed that both saturated and unsaturated conductivity of compacted and non-compacted soils can be predicted using BD data, but it remains to be seen whether TP can improve the predictions compared to the use of BD.

Another issue closely associated with infiltration is the presence of surface seals, but this was not examined in this study. The infiltration tests were carried out in the banana rows, which were mostly covered with banana residues, and the opportunity for clay dispersion and subsequent seal formation, was therefore limited. Further, rain-drop impact energy under banana row canopy may be low; thus, we suggest that the opportunity for clay dispersion and consequent surface seal formation was limited. Therefore, we claim the differences in infiltration processes between banana and the corresponding forest were largely due to changes in TP. In this regard it noteworthy that though surface seal might not have been an issue, infilling of interaggregate pore-space even by few dispersed particles and compaction of infilled particles might have reduced TP and consequently the conductivity of the infiltrated water and its retention (Augeard *et al.* 2008).





**Fig. 3.** Comparisons of porosity distributions in the interrows and rows of banana in the different grass-cover treatments and the interrows of control compared with grass-cover treatment.

### Grass-cover experiments

The results from the grass-cover experiment (Fig. 3a–c) indicates that TP in the banana rows was significantly higher than TP in the corresponding interrows of bare control or pinto peanut or carpet grass-covers. This suggests that 18 months of pinto peanut or carpet grass-cover in the interrows was not effective in producing changes in porosity. Alternatively, the non-significant difference in TP between the banana rows and the interrows of indigenous grass indicates that this volunteer species was effective in reducing the impact of wheel traffic-induced decreases in TP. On average there were 6% less pores in the interrows than the rows, exclusive of under indigenous grass-cover. The non-significant difference in TP between the rows and interrows under indigenous grass-cover indicates that it was effective in preventing this 6% loss associated with WTS-induced stress.

Due to budgetary and other constraints, we could not carry out measurements on the changes in aggregate size distributions, infiltration, OC, and aggregating cation concentration (e.g.  $\text{Ca}^{2+}$ ) before and after grass-cover establishment to provide additional support to the changes in TP as affected by grass-covers. Though the results from other studies are not directly applicable to our banana system, nevertheless some general insight can be gained from the work of others (e.g. Hulugalle 1992; Kang *et al.* 1997). For example, Hulugalle (1992) reported that 17 months after the establishment of 15 leguminous and graminaceous species in a highly degraded and compacted soil in south-western Nigeria, significant increases in macroporosity or reduction in compaction and high levels of  $\text{Ca}^{2+}$  occurred in plots on which plant materials were returned compared with continuously cropped soil. The author also reported that natural regrowth (native

species) was more effective or better than planted species in improving soil physical and chemical properties and the need for exotic plant species for ameliorating highly degraded alfisols was unnecessary. Kang *et al.* (1997), however, reported that even after 4 years of fallow with selected pasture they did not find any significant improvement in BD and concluded longer fallow may be needed to amend soil physical conditions in highly eroded and compacted Oxic Paleustalf in south-western Nigeria. Though Hulugalle (1992) and Kang *et al.* (1997) results are compatible with ours with regard to the effectiveness of native grass-cover, the time taken to be effective is much shorter in our study than the other studies. Nevertheless the time component in our study is comparable to that of Hulugalle (1992).

There are 2 aspects that need attention here with regard to the effectiveness of indigenous grasses. Firstly, the indigenous species were observed to establish and provide full cover much faster than other cover. Secondly, the root system of the indigenous grasses appeared to be denser and was able to provide a better cushioning effect against wheel traffic. It is, however, not known whether the other 2 grass-covers will produce similar results after >18 months. We believe the beneficial effect of grass-covers, particularly the indigenous grass-cover, was mostly due to reduction in WTS on TP than to bio-chemical processes associated improvements in aggregation.

### Conclusions

Contrary to the general belief that compaction under cropping is mostly confined to <0.50 m, we show the impact of wheel traffic associated stress (WTS) on total porosity (TP) can extend to >1.0 m. We propose a modified model to estimate threshold

compaction index ( $DI_c$ ) and show the  $DI_c$  around 0.81–0.83 as a threshold, regardless of soil type. Though the WTS impact on porosity is mostly believed to be on structural porosity, we show it can also affect textural porosity. We show that high organic matter (OC) content alone may not be sufficient to overcome the impact of WTS-induced reductions in TP; rather, substantial reductions in WTS play a larger role in this regard than OC. The link between TP and WTS, OC, clay + silt, the interactions between the latter two, and the infiltration parameters suggest the low-technology and low-cost TP, possesses the ability to integrate and reflect several soil physical properties and functions/processes. Therefore, we propose that TP can be used as a low-cost low-technology soil physical health quality indicator.

Our results show that interrow grass-covers were effective to resist, and recover from, WTS-induced reduction in TP. The recovery, at least partially, in TP after 18 months of interrow grass-covers indicates management options are available to retard the WTS-induced reductions in TP. In this regard the indigenous grass-cover was found to be the most effective in this wet environment.

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### References

- Arshad MA, Coen GM (1992) Characterisation of soil quality: physical and chemical criteria. *American Journal of Alternative Agriculture* **7**, 25–31.
- Assouline S (2006) Modelling the relationship between soil bulk density and the hydraulic conductivity functions. *Vadose Zone Journal* **5**, 697–705. doi: 10.2136/vzj2005.0084
- Augeard B, Bresson LM, Assouline S, Kao C, Vauclin M (2008) Dynamics of soil surface bulk density: Role of water table elevation and rainfall duration. *Soil Science Society of America Journal* **72**, 412–423. doi: 10.2136/sssaj2006.0429
- Baker J (2003) A report on the study of land-sourced pollutants and their impacts on water quality in and adjacent to the Great Barrier Reef. Department of Primary Industries, Brisbane, Australia.
- Bell MJ, Bridge BJ, Harch GR, Orange DN (1997) Physical rehabilitation of degraded krasnozems using ley pastures. *Australian Journal of Soil Research* **35**, 1093–1113. doi: 10.1071/S97005
- Bell MJ, Moody PW, Yo SA, Connolly RD (1999) Using active fractions of soil organic matter as indicators of the sustainability of Ferrosol farming systems. *Australian Journal of Soil Research* **37**, 279–287. doi: 10.1071/S98064
- Blair N, Crocker GJ (2000) Crop rotation effects on soil carbon and physical fertility of two Australian soils. *Australian Journal of Soil Research* **38**, 71–84. doi: 10.1071/SR99064
- Bouwer H (1986) Intake rate: cylinder infiltrometer. In 'Methods of soil analysis, Part 1, Physical and mineralogical methods'. (Ed. A Klute) (ASA/SSSA: Madison, WI)
- Bridge BJ, Bell MJ (1994) Effect of cropping on the physical fertility of krasnozems. *Australian Journal of Soil Research* **32**, 1253–1273. doi: 10.1071/SR9941253
- Brodie J, McKergow, Prosser IP, Furnas M, Hughes AO, Hunter H (2003) Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area. ACTFR Report 03/11. Townsville, Australia.
- Bruand A, Cousin I (1996) Variation of textural porosity of a clay-loam soil during compaction. *International Journal of Rock Mechanics* **33**(5), 202A. doi: 10.1016/0148-9062(96)89898-6
- Congdon A, Herbohn JL (1993) Ecosystem dynamics of disturbed and undisturbed sites in north Queensland wet tropical rainforest. I. Florestic composition and climate change. *Journal of Tropical Ecology* **9**, 349–363. doi: 10.1017/S0266467400007409
- Dexter AR (2004) Soil physical quality Part 1. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma* **120**, 201–214. doi: 10.1016/j.geoderma.2003.09.004
- Doran JW, Coleman DC, Bezdicsek DF, Stewart BA (1994) Defining and assessing soil quality. In 'Defining soil quality for a sustainable environment'. Soil Science Society of America, Special Publication No. 35. (SSSA: Madison, WI)
- Drewry JJ, Cameron KC, Buchan GD (2008) Pasture yield and soil physical property responses to soil compaction from treading and grazing—a review. *Australian Journal of Soil Research* **46**, 237–256. doi: 10.1071/SR07125
- Fies JC (1992) Mercury of soil textural porosity relative to skeleton particle size, using mercury porosimetry. *Soil Science Society of America Journal* **56**, 1062–1067.
- Gee GW, Bauder JW (1986) Particle-size analysis. In 'Methods of soil analysis. Part 1'. 2nd edn. Agronomy Monograph 9. (Ed. A Klute) pp. 383–411. (ASA and SSSA: Madison, WI)
- Gregorich ED (1996) Soil quality: a Canadian perspective. In 'Soil quality indicators for sustainable agriculture in New Zealand. Proceedings of Workshop for MAF Policy by the Lincoln Soil Quality Research Centre'. Lincoln University, New Zealand. Lincoln Soil Quality Research Centre Publication No. 1. (Lincoln University: Lincoln, NZ)
- Hulugalle NR (1992) Amelioration of highly degraded tropical alfisol by planting. I. Changes in soil physical and chemical properties. *Land Degradation & Development* **3**, 141–152. doi: 10.1002/ldr.3400030302
- Isbell RF (1994) Krasnozems – a profile. *Australian Journal of Soil Research* **32**, 915–929. doi: 10.1071/SR9940915
- Isbell RF (1996) 'The Australian soil classification.' (CSIRO Publishing: Collingwood, Vic.)
- Kang BT, Salako FK, Akobundu IO, Pleysier JL, Chanu JN (1997) Amelioration of a degraded Oxic Paleustalf by leguminous and natural fallow. *Soil Use and Management* **13**(3), 130–136. doi: 10.1111/j.1475-2743.1997.tb00572.x
- Kernot I, Lindsay S, Campagnolo D, Daniells J, Evans D, *et al.* (1998) Agrilink tropical banana information kit. Department of Primary Industries, Queensland, QAL9807.
- Kostiakov AN (1932) On the dynamics of coefficient of water-percolation in soils and the necessity of studying it from a dynamic point of view for purposes of ameliorations. *Transactions Communications of the International Society of Soil Science* **6**, 267–272.
- McGarry D (1990) Soil compaction and cotton growth on a vertisol. *Australian Journal of Soil Research* **28**, 869–877. doi: 10.1071/SR9900869
- Murtha GG (1986) Soils of Tully–Innisfail area, North Queensland. CSIRO Division of Soil, Divisional Report No. 82.
- Prove BG, Loch RJ, Foley JL, Anderson VJ, Younger DR (1990) Improvements in aggregation and infiltration characteristics of a krasnozem under maize with direct drill and stubble retention. *Australian Journal of Soil Research* **28**, 577–590. doi: 10.1071/SR9900577
- Reichert JM, Suzuki LEAS, Reinert DJ, Horn R, Hakansson I (2009) Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. *Soil & Tillage Research* **102**, 242–254. doi: 10.1016/j.still.2008.07.002
- Richard G, Boziard H, Roger-Estrade J, Boiffin J, Guerif J (1999) Field study of soil compaction due to traffic in northern France: pore space and morphological analysis of the compacted zones. *Soil & Tillage Research* **51**, 151–160. doi: 10.1016/S0167-1987(99)00058-6

- SAS (1991) 'SAS/STAT Procedure for Personal Computers, Version 5.' (Statistical Analysis Systems Institute, Inc.: Cary, NC)
- Stange FC, Horn R (2005) Modeling soil water retention curve for conditions of variable porosity. *Vadose Zone Journal* **4**, 602–613. doi: 10.2136/vzj2004.0150
- Talbot LM, Turton SM, Graham W (2003) Trampling resistance of rainforest soils and vegetation in the wet tropics of north east Australia. *Journal of Environmental Management* **69**, 63–69. doi: 10.1016/S0301-4797(03)00119-1
- Warrick AW, Lomen DO, Yates RS (2005) A generalized solution to infiltration. *Soil Science Society of America Journal* **49**, 34–38.
- Zou C, Sand R, Buchan G, Hudson I (2000) Least limiting water range: a potential indicator of physical quality of forest soils. *Australian Journal of Soil Research* **38**, 947–958. doi: 10.1071/SR99108

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