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Least limiting water range: a potential indicator of physical quality of forest soils

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Abstract

The interactions of the 4 basic soil physical properties—volumetric water content, matric potential, soil strength, and air-filled porosity—were investigated over a range of contrasting textures and for 3 compaction levels of 4 forest soils in New Zealand, using linear and non-linear regression methods. Relationships among these properties depended on texture and bulk density. Soil compaction increased volumetric water contents at field capacity, at wilting point, and at the water contents associated with restraining soil strength values, but decreased the water content when air-filled porosity was limiting. The integrated effect of matric potential, air-filled porosity, and soil strength on plant growth was described by the single parameter, least limiting water range (LLWR). LLWR defines a range in soil water content within which plant growth is least likely to be limited by the availability of water and air in soil and the soil strength. Soil compaction narrowed or decreased LLWR in most cases. In coarse sandy soil, initial compaction increased LLWR, but further compaction decreased LLWR. LLWR is sensitive to variations in forest management practices and is a potential indicator of soil physical condition for sustainable forest management.

Additional keywords: soil volumetric water content, soil matric potential, soil strength, soil air-filled porosity, soil moisture characteristic curve, soil strength characteristic curve.

Introduction

Increasing human populations, decreasing resources, social instability, and environmental degradation pose serious threats to the natural processes that sustain the global ecosphere and life on earth (Doran 1996). Much of the debate has been and still is about forests, their sustainable use, and their pivotal role in land management decisions (Nambiar 1996). Sustainable forestry depends on the wise management of soil (Powers and Morrison 1996), and a central goal of management is to maintain and enhance the quality of the soil resource base in perpetuity. To achieve this goal, forest management strategies and operations should ensure that the soil base is protected. As such, soil-based sustainability indicators should be developed as a guideline for forest management practices.

According to Doran and Parkin (1994), soil quality indicators are basically classified into 3 categories: physical, chemical, and biological. Attempts to assess soil quality involve direct measurement of some of these properties (e.g. texture, organic matter content, hydraulic conductivity, water-holding capacity, bulk density, and soil strength), along with an assessment of soil conditions (e.g. fertility) to integrate some of these properties. The aggregate of measurements of the individual soil properties probably is not a useful indicator because the large number of individual properties makes it complex

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to interpret. Another limitation is that, even though the aggregate is a composite measure, it does not account for any interactions between properties. Ideally, indicators of soil condition should be few in numbers and subsume as many properties as possible. Gregorich (1996) considered that the best characterisation of interactions is achieved by aggregating information to describe a process or function of soil.

An attempt to integrate several physical properties into a single parameter called the non-limiting water range (NLWR) was proposed by Letey (1985). NLWR represents the volumetric water content range where root growth is not affected by air-filled porosity, water potential, or soil strength. The concept of NLWR assumes that the range of soil water available for plant use may be limited by poor aeration at the wet end and/or high soil strength at the dry end, rather than being defined by the traditional field capacity and wilting point. More recently, the term least limiting water range (LLWR) has been introduced (da Silva *et al*. 1994). LLWR is numerically equal to NLWR and is probably a more appropriate term because it does not imply that water use suddenly switches on and off at prescribed limiting values. LLWR integrates 4 factors directly associated with plant growth into a single variable which may be a useful index of the physical quality of a soil for crop production (Gregorich 1996). LLWR is the range in soil water content which is defined (*a*) at the upper end by the soil water content at an arbitrary value of non-limiting air-filled porosity (0.10 cm^3/cm^3) or at nominal field capacity (–0.01 MPa), whichever is the lower, and (*b*) at the lower end by the water content at an arbitrary value of limiting soil strength (say 3.0 MPa) or the water content at nominal wilting point (–1.5 MPa), whichever is the greater.

Soil compaction is known to reduce the site productivity of forests (Froehlich *et al.* 1984), including *Pinus radiata* D Don (radiata pine) plantations (Greacen and Sands 1980; Murphy *et al*. 1997). Soil quality indicators to monitor the soil compaction process and its impact on site productivity are needed. The aim of this study was to determine how LLWR is affected by compaction in some important forest soils in New Zealand and to assess its potential as an indicator of soil physical condition. Four soil types of contrasting texture were used. Both linear and non-linear regression techniques were used to establish soil moisture characteristic curves, and soil strength characteristic curves at 3 levels of compaction for each soil. The change of LLWR was then evaluated under the different compaction levels to demonstrate its relevance to management practices.

Materials and methods

Four soil types of contrasting textures were collected from the top 20 cm of soil after the surface litter and debris were removed from radiata pine plantations of Rayonier NZ. These were a pumice (loamy sand), argillite (loam), ash (sandy clay loam), and loess soil (silty clay) (Zou 1999). All the soils were sieved through a 2-mm sieve and the gravimetric water content (θ_m) at sampling was determined. The particle size distribution and particle density were determined by the methods described by McIntyre and Loveday (1974). Total porosity (= saturated volumetric water content) was calculated from particle density for a particular bulk density. These soils were uniformly packed into steel rings (inner diameter 48 mm and depth 15 mm) using the method described by Misra and Li (1996). The corresponding weight of soil (of known θ_m) was packed into the ring (of known volume) to achieve the required bulk density. Three bulk density classes were used for each soil type with 3 replicates for each density. The density classes (low, medium, high) were representative of low, medium, high compaction situations in the field.

Soil water retention studies

Repacked soil samples were placed in a water bath to saturate overnight. The saturated soil samples were placed in a pressure plate apparatus to equilibrate the soils to selected water potentials by the method described by Merwe (1990). After equilibration at each matric potential (Ψ_m), the samples were weighed immediately to calculate volumetric water content (θ_v) at this Ψ_m. This process was repeated at 7 Ψ_m

levels: –0.01, –0.03, –0.07, –0.1, –0.2, –0.5, and –1.5 MPa. The time for equilibrium ranged from 1–2 days for –0.01 MPa to about 4 weeks for –1.5 MPa.

Determination of soil strength

Immediately following the determination of volumetric water content, the equilibrated samples were used to determine soil strength by a custom-designed laboratory cone penetrometer[#]. This penetrometer had a constant speed/variable torque motor that pushed the metal probe into the soil sample at a constant speed of 3 mm/min. The force generated from the probe was measured by an electronic balance and recorded every 10 sec (each 0.5 mm depth) and transferred to an Excel worksheet using the software Wedge (THL Enterprises). In this study, the metal probe had a cone base diameter of 2.0 mm and a tip semi-angle of 30 degrees. The soil strength (Q, MPa) was calculated from the following equation:

$$Q = Wt \times g/\pi r^2 \tag{1}$$

where Wt is weight measured by electronic balance (kg), g is gravitational acceleration (9.8 m/s^2), and r is the radius of the cone base of the metal probe (mm).

Soil strength was taken as the mean of 5 soil strength values recorded between 10 and 15 mm depth (Misra and Li 1996).

Determination of soil air-filled porosity

Aeration is quantitatively represented by the air-filled porosity (ε_a), calculated by Eqn 2:

$$\varepsilon_a = 1 - (\rho_b/\rho_s) - \theta_v \tag{2}$$

where θ_v is volumetric water content (cm^3/cm^3), ρ_b is soil bulk density (g/cm^3), and ρ_s is particle density (g/cm^3).

Statistical analysis

A widely used analytical model for the soil moisture characteristic curve is the Brooks–Corey power-function (Brooks and Corey 1964). A simpler form of this function was given by Cosby *et al.* (1984) and Campbell (1985) as:

$$|\Psi_m| / |\Psi_e| = (\theta_v/\theta_s)^b \text{ for } |\Psi_m| > |\Psi_e| \tag{3}$$

where $|\Psi_m|$ (MPa) is suction (the negative of matric potential), and θ_v is volumetric water content (= θ_s at saturation). $|\Psi_e|$ and b are adjustable parameters.

Buchan and Grewal (1990) used the log-transformation of this power function (Eqn 4) and demonstrated that this gave a good fit to observations over varying ranges of soil matric potential:

$$\ln |\Psi_m| = \alpha + \beta \ln (\theta_v/\theta_s) \tag{4}$$

The measured paired θ_v and $|\Psi_m|$ data were used to fit the linear regression model (Eqn 4) using SAS REG procedure (SAS System for Windows v 6.12). A non-linear modelling technique (SAS NLIN Proc) was used to fit the relationship between soil strength and volumetric water content using the residual of mean square (RMS) as a model selection criterion.

Results and discussion

The values of soil bulk density (ρ_b) used in this study corresponding to low, medium, and high values of compaction may seem to be unreasonably low compared with to global averages, which usually exceed 1.0 g/cm^3. da Silva *et al.* (1994) investigated LLWR in a loamy sand and a silt loam over a combined range of ρ_b of 1.25–1.7 g/cm^3. However, the lower values of ρ_b reported in our study are characteristic of those found in the field for our soils. For example, McMahon *et al.* (1999) found that the bulk density of the pumice soil used in this study increased from 0.68 in the undisturbed state to 0.89 g/cm^3 after 20–50 passes of harvesting machinery. The soil strengths increased from 0.4 to 4.0 MPa over this range of bulk densities. In our study, the low and high values of ρ_b for pumice

[#] Designed by R. Misra (University of the Sunshine Coast, Australia) and manufactured by Precision Engineering, Australia.

Table 1. Regression models of soil matric potential (Ψ_m) and volumetric water content (θ_v) for soils of contrasting textures at three bulk density (ρ_b) levels

s.e., standard error

ρ_b (g/cm^3)	Soil moisture characteristic curves $\ln \lvert\Psi_m\rvert = \alpha + \beta \ln(\theta_v/\theta_s)$ (n = 21, P < 0.0001) α ± s.e.	 β ± s.e.	R^2
	Pumice (loamy sand)		
0.70	–8.77±0.17	–4.47±0.11	0.99
0.80	–8.27±0.23	–4.77±0.17	0.98
0.85	–7.76±0.20	–4.79±0.16	0.98
	Argillite (loam)		
0.90	–7.76±0.22	–6.50±0.24	0.97
1.0	–6.86±0.17	–6.78±0.24	0.98
1.1	–5.86±0.12	–7.04±0.22	0.98
	Ash (sandy clay loam)		
0.70	–9.13±0.25	–4.97±0.19	0.98
0.80	–8.76±0.32	–5.58±0.25	0.96
0.85	–8.64±0.42	–6.46±0.44	0.93
	Loess (silty clay)		
0.85	–10.59±0.30	–10.08±0.35	0.98
0.95	–9.91±0.33	–12.06±0.51	0.97
1.05	–7.99±0.31	–13.05±0.67	0.95

were 0.70 and 0.85 g/cm^3 and penetrometer soil strength values were 0.48 and 3.66 MPa. R. C. Simcock, C. W. Ross, and J. L. Dando (pers. comm.) measured the bulk density of ash soils in experiments in the field where they imposed a series of soil compaction treatments. They found that the range in ρ_b was 0.57–0.70 g/cm^3, an even lower range than that used for ash in our study (0.70–0.85 g/cm^3). Field values of bulk density for argillite and loess are also known to be similar to the range of values used for these soils in our study. The soils in our study had different, and lower than normal, particle densities, due to a combination of high organic matter contents and low mineral particle densities. Pumice, for example, is derived from volcanic tephra and has lower mineral density than normal soil parent material. Also, R. C. Simcock, C. W. Ross, and J. L. Dando (pers. comm.) measured particle densities of 2.28–2.41 g/cm^3 for 0–75 mm depth in an ash soil similar to that used in this study.

Soil moisture characteristic curves

All the soil texture and bulk density data satisfactorily fitted the linear regression model of Buchan and Grewal (1990), with θ_v highly significant (P < 0.0001; 0.93 ≤ R^2 ≤ 0.99). The estimates of α and β and their standard errors are given in Table 1.

The lower (i.e. the more negative) the value of β, the harder it is to extract water from the soil at a given water content. The magnitude of β decreased with increased coarseness of soil texture, and increased with increasing bulk density in all soils. At the same soil volumetric water content, the suction in compacted soil was higher than in less compacted soil (Table 1). The data for moisture characteristic curves in Table 1 can be transformed into the exponential form (Eqn 3) to demonstrate the change in matric potential with change in water content (Fig. 1).

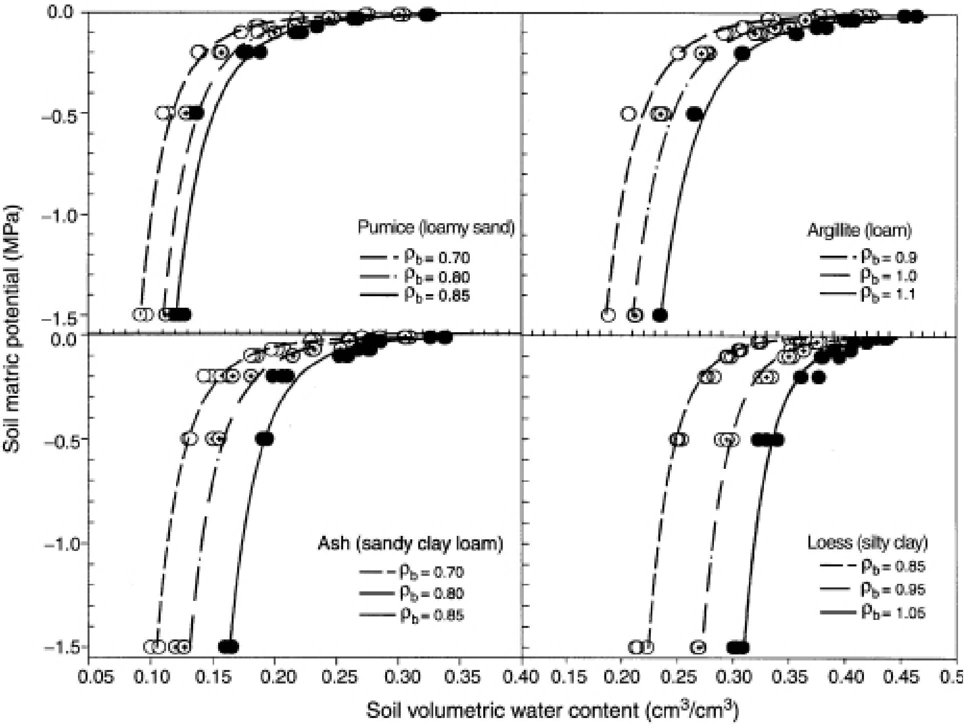

Fig.1. Relationships between soil matric potential (Ψ_m) and volumetric water content (θ_v) for soils of contrasting textures at three bulk densities (ρ_b). Curves are drawn from Eqn 3.

Soil strength characteristic curves

The relationship between soil strength and volumetric water content, θ_v, was established for each of the 3 bulk densities of the 4 soil types over the range between field capacity and wilting point (Fig. 2). Soil strength increased as soil water content decreased (Fig. 2). This relationship is more complicated than the simple linear relationship suggested by Khristov and Khristov (1981). By using the SAS non-linear regression procedure, the original data were best fitted by a logarithmic model:

$$Q = a \ln\theta_v + b \tag{5}$$

where Q is soil strength (MPa), θ_v is soil volumetric water content, and *a* and *b* are regression coefficients.

The estimates of *a* and *b* varied with both soil type and bulk density (Table 2). The parameter *a* represents the rate of increase in soil strength with the natural log of volumetric water content and it was influenced more by bulk density than soil type. The value of *a* decreased 3.2, 4.8, 6.4, and 5.6 times from low to high bulk densities for the pumice, argillite, ash, and loess, respectively. By contrast, the value of *a* decreased 3, 2.9, and 5.1 times between soils for low, medium, and high values of bulk density respectively. This suggests that the rate of increase in soil strength as soil dries is more sensitive to change in bulk density in a given soil than to changes in soil type or texture. For a given soil, *a* decreased with increasing soil bulk density (Table 2). The rate of increase in soil strength with decreasing soil water content increased with increasing

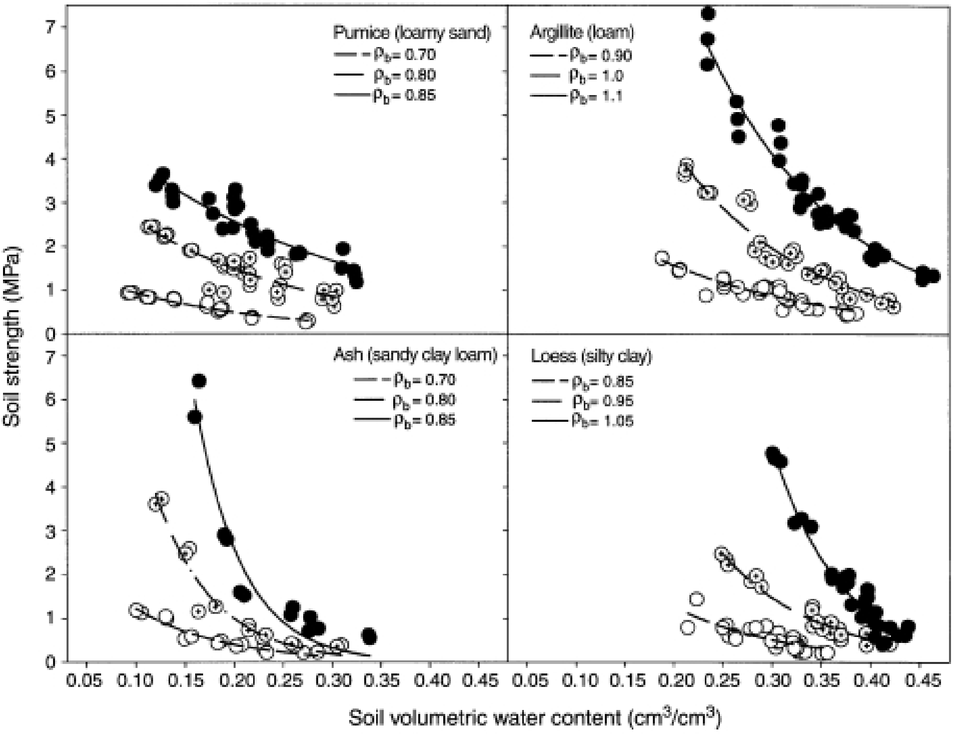

Fig. 2. Relationship between soil strength (Q) and soil volumetric water content (θ_v) for four soil

bulk density (Fig. 2). For each bulk density state (low, medium, high), *a* was mostly in the order loess < argillite < ash < pumice (Table 2). This suggests that the rate at which soil strength increased with decreasing water content increased as the soils became finer in texture.

Soil air-filled porosity and volumetric water content

In a given soil, soil particle density, ρ_s, is constant. The particle density values of pumice, argillite, ash, and loess are 2.44, 2.55, 2.41, and 2.53 g/cm^3, respectively. At a given bulk density, ρ_b, soil air-filled porosity, ε_a, is a linear function of soil volumetric water content, θ_v, and can be calculated by Eqn 2. For each soil at different bulk densities the equation connecting ε_a and θ_v was established and ε_a at field capacity (ε_{afc}) and wilting point (ε_{awp}) were calculated and are listed in Table 3.

At field capacity, εa ranged from just <0.10 cm^3/cm^3 in argillite (ρ_b = 1.1) to 0.44 cm^3/cm^3 in pumice (ρ_b = 0.70). At wilting point εa ranged from 0.27 cm^3/cm^3 in loess (ρ_b = 1.05) to 0.62 cm^3/cm^3 in pumice (ρ_b = 0.7).

LLWR: integrated effects of soil air, soil matric potential, and soil strength

Root growth of radiata pine was reported to be seriously restricted when soil strength was above 3.0 MPa (Sands *et al.* 1979). To estimate the LLWR in soil, soil water content values, θ_v, were calculated at the following points: 0.10 cm^3/cm^3 air-filled porosity, field capacity (–0.01 MPa matric potential), wilting point (–1.5 MPa matric potential), and the

Table 2. Parameters for the logarithmic model between soil strength (Q) and soil volumetric water content (θ_v) for soils of contrasting textures and bulk densities (ρ_b)

s.e., standard error; RMS, residual mean square

ρ_b (g/cm^3)	Estimated parameters *a* ± s.e.	 *b* ± s.e.	RMS	θ_v range
		Pumice (sandy loam)		
0.70	–0.67±0.04	–0.64±0.08	0.006	0.09–0.28
0.80	–1.58±0.14	–1.06±0.23	0.059	0.11–0.31
0.85	–2.17±0.17	–0.95±0.27	0.078	0.12–0.33
		Argillite (loam)		
0.90	–1.65±0.11	–1.09±0.14	0.017	0.19–0.39
1.0	–4.63±0.24	–3.49±0.28	0.072	0.21–0.43
1.1	–7.96±0.36	–5.30±0.39	0.147	0.24–0.47
		Ash (sandy clay loam)		
0.70	–1.02±0.09	–1.21±0.16	0.012	0.10–0.28
0.80	–3.36±0.55	–4.11±0.87	0.256	0.13–0.31
0.85	–6.61±1.08	–7.50±1.56	0.091	0.16–0.34
		Loess (silty clay)		
0.85	–1.99±0.27	–1.86±0.32	0.022	0.22–0.36
0.95	–4.12±0.57	–3.31±0.59	0.087	0.27–0.41
1.05	–11.08±0.79	–8.96±0.75	0.098	0.31–0.45

soil strength restriction limit (3.0 MPa) considered to seriously restrict root growth. Based on the soil moisture characteristic curves (Table 1), soil strength characteristic curves (Table 2), and the relationship between θ_v and air-filled porosity (Table 3), these θ_v values were calculated (Table 4). LLWR was calculated as the difference between the lower of the θ_v at an air-filled porosity of 0.10 cm^3/cm^3 or at field capacity, and the higher of the θ_v at a soil strength of 3.0 MPa or at wilting point (Table 4).

LLWR decreased with increasing bulk density in the medium-textured soils (argillite and ash), which is similar to the result reported by da Silva *et al.* (1994) in a silt loam soil in Canada. However, in the coarse pumice soil, medium compaction increased the LLWR slightly because the increase in water content at field capacity was greater than that at wilting point. da Silva *et al.* (1994) also reported that, when increasing the bulk density of a coarse loamy sand, the LLWR first increased and then declined at higher bulk densities.

Fig. 3 describes the interaction of soil physical properties in the compaction process and the resulting modification to LLWR in the pumice soil. In a loose soil with low bulk density of 0.7 g/cm^3 (Fig. 3*a*), soil is free from soil strength and aeration problems, and LLWR equals the 'available water capacity' (AWC), which is the water content between field capacity and wilting point. When this soil is slightly compacted (ρ_b = 0.8, Fig. 3*b*), 4 effects are observed. Firstly, the water content associated with limiting air-filled porosity is reduced, but it is still over the field capacity point and therefore does not influence LLWR. Secondly, θ_v at field capacity (θ_{vfc}) increases, i.e. the soil's ability to retain water is enhanced. Thirdly, θ_v at wilting point (θ_{vwp}) also increases, partly offsetting the increase in θ_{vfc}. Finally, there is a marked increase of soil strength as the soil strength restriction line moves quickly toward higher water contents, but is still below the wilting point. The most significant change with further compaction (ρ_b = 0.85, Fig. 3*c*) is that the soil strength line rapidly moves inside the wilting point line and the limiting water content at the lower end of LLWR becomes defined

Table 3. Relationship between soil air-filled porosity (ε_a) and soil volumetric water content (θ_v) and calculated soil air-filled porosity at field capacity (–0.01 MPa, ε_{afc}) and wilting point (–1.5 MPa, ε_{awp})

ρ_b (g /cm^3)	$\varepsilon_a = 1-(\rho_b/\rho_s)-\theta_v$	ε_{afc}	ε_{awp}
	Pumice (loamy sand)		
0.7	$0.714-\theta_v$	0.435	0.622
0.8	$0.673-\theta_v$	0.364	0.562
0.85	$0.652-\theta_v$	0.319	0.531
	Argillite (loam)		
0.9	$0.647-\theta_v$	0.253	0.461
1	$0.608-\theta_v$	0.176	0.398
1.1	$0.569-\theta_v$	0.096	0.334
	Ash (sandy clay loam)		
0.7	$0.709-\theta_v$	0.425	0.604
0.8	$0.668-\theta_v$	0.357	0.536
0.85	$0.647-\theta_v$	0.307	0.483
	Loess (silty clay)		
0.85	$0.663-\theta_v$	0.299	0.439
0.95	$0.624-\theta_v$	0.212	0.351
1.05	$0.584-\theta_v$	0.138	0.274

Table 4. Critical points for determination of least limiting water range (LLWR) for root growth

The values shown represent volumetric water content (θ_v) at each point. Values in italics represent water content where the lower limit of LLWR is determined by soil strength rather than wilting point

	Pumice			Argillite			Ash			Loess		
ρ_b (g/cm^3)	0.7	0.8	0.85	0.9	1.0	1.1	0.7	0.8	0.85	0.85	0.95	1.05
Ψ_m = –0.01MPa (θ_{vfc})	0.28	0.31	0.33	0.39	0.43	0.47	0.42	0.48	0.51	0.36	0.43	0.44
Ψ_m = –1.5 MPa (θ_{vwp})	0.09	0.11	0.12	0.18	0.21	0.23	0.26	0.30	0.32	0.22	0.26	0.30
Q = 3 MPa (strength limit)	0.03	0.09	*0.16*	0.14	*0.24*	*0.33*	0.20	*0.33*	*0.38*	0.17	0.24	*0.33*
ε_a = 0.10 (aeration limit)	0.61	0.57	0.55	0.53	0.49	0.45[A]	0.59	0.55	0.53	0.56	0.52	0.48
LLWR	0.19	0.20	0.17	0.21	0.19	0.12	0.16	0.15	0.13	0.14	0.17	0.11

[A] Water content where the higher limit of LLWR is determined by air-filled porosity rather than field capacity.

by soil strength instead of wilting point. This trend is similar in soils with different textures. In the other 3 finer textured soils, as bulk density increases, θ_{vfc} increases and approaches the aeration limit (ε_α = 0.10 cm^3/cm^3). In the argillite at its highest bulk density, the aeration limit falls below θ_{vfc}, and hence sets the upper limit for LLWR. Increasing soil bulk density will further compress this distance and the aeration limit will move inside the water content at field capacity and cause partial anaerobic conditions.

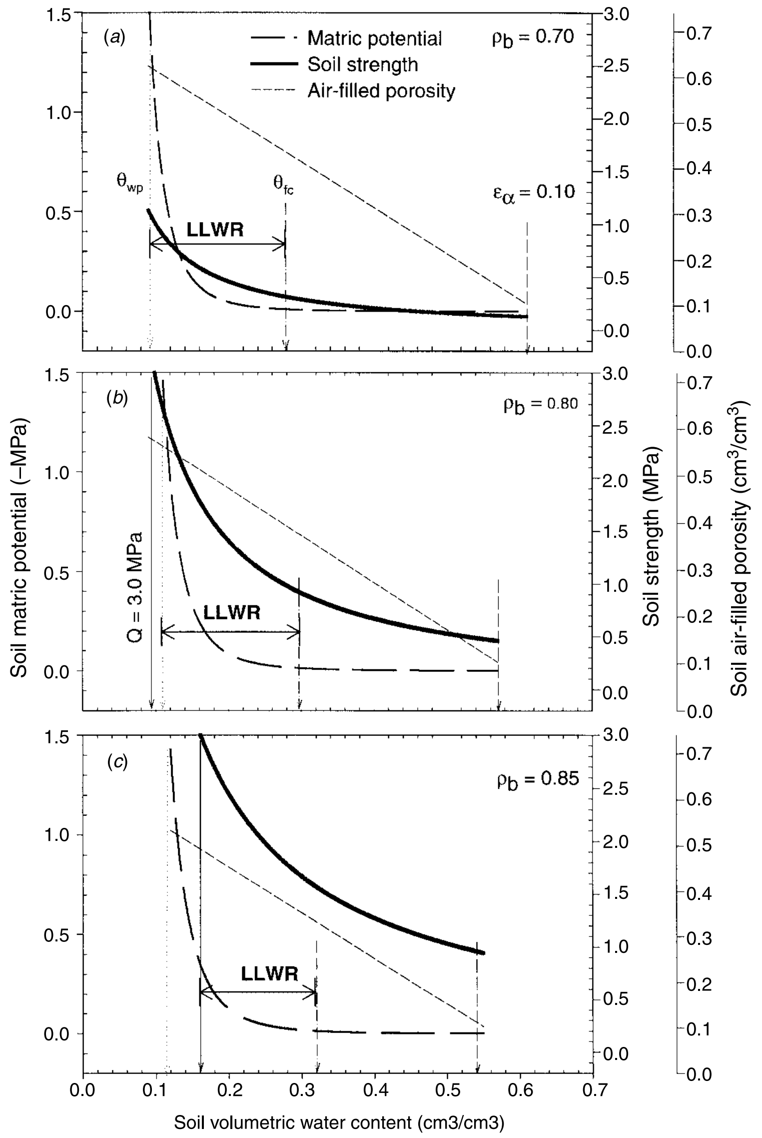

Fig. 3. Change in LLWR with increase in soil bulk density (ρ_b) in pumice soil.

Topp *et al.* (1994) used the NLWR (numerically the same as LLWR) concept in Canada with different textures and soil types, and concluded that in nearly all cases the NLWR was less than the traditional available water capacity (AWC, the difference between field capacity and wilting point). About 30% of the soil horizons showed inadequate aeration, and >90% of the horizons showed >2.0 MPa penetration resistance at water potential above –1.5 MPa. This suggests that the value of NLWR differs significantly from that of AWC and can better define the physical suitability of a soil for plant growth, and is a potential soil quality indicator.

Recently, Penfold (1999) showed that root growth of radiata pine seedlings in a range of soil textures was close to zero at air-filled porosities <0.05 cm^3/cm^3, after which it increased asymptotically and gradually to a maximum around 0.16 cm^3/cm^3. There is, therefore, no sudden arbitrary limit of 0.10 cm^3/cm^3 air-filled porosity but it is not a grossly inaccurate assumption for radiata pine and it still could be useful as a delimiting value.

Roots also do not suddenly stop growing at 3.0 MPa penetrometer soil strength, or any other value for that matter. Root growth of radiata pine decreases exponentially with increasing soil strength and indeed the rate of decrease in root growth is greater at lower than at higher soil strengths (Zou 1999). Also, root elongation rate of radiata pine is known to decrease as soil water content decreases from field capacity to wilting point (Zou 1999). Here again, it is not correct to assume that limiting values of water potential and soil strength have a sudden impact.

A weakness in the concept of NLWR (and LLWR) is that it assumes that limiting values of air-filled porosity, water potential, and soil strength are suddenly rather than gradually imposed, and are independent of soil type, plant species, and other variables (e.g. soil temperature). Changing the name from NLWR to LLWR acknowledges these weaknesses (da Silva *et al.* 1994) but does nothing to actually improve it as an indicator. However, LLWR can be used as a generic indicator of soil physical condition, and it particularly has advantages in monitoring change in soil physical condition over time.

LLWR and soil texture

LLWR usually decreased with compaction. LLWR decreased when pumice and loess were compacted from medium to high bulk density and when ash and argillite were compacted from low through medium to high bulk density (Fig. 4). However, in the coarse-textured pumice and the fine-textured loess, an increase in soil bulk density from low to medium levels actually increased LLWR (Fig. 4). The increase in LLWR in pumice occurred because the reduction of macropores caused an increase in the number of middle-sized pores. The increase in LLWR in loess occurred because the rate of increase in soil strength with increasing bulk density was slowest in the fine-textured soil.

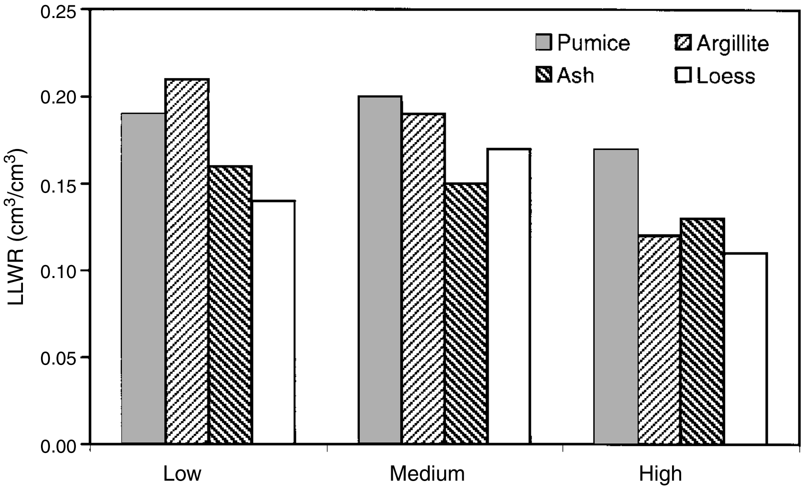

Fig. 4. Change in LLWR with compaction degree in different soil types.

LLWR—a potential forest soil quality indicator

Cameron *et al.* (1996) considered that soil quality indicators for sustainable agriculture in New Zealand should be scientifically valid, cost-effective to measure, where possible a component of an existing data set, and sensitive to variations in management, and should correlate well with agricultural ecosystem processes. A forest plantation system functions similarly to an agricultural system, except for its relatively long rotation. As such, most soil quality indicators for agricultural systems are also acceptable for sustainable forest management practice with minor change.

LLWR is controlled by soil-based processes and is related to plant physiological processes. Management practices that might change soil structure and soil bulk density, like site preparation and harvesting, will be reflected in changes of LLWR. Water relations, soil aeration, and soil mechanical condition are important components of ecosystem processes, and LLWR integrates the effects of these factors and so may be an important indicator to describe ecosystem processes. Therefore, LLWR is a potential soil quality indicator for sustainable soil management.

LLWR—implication and limitation

Least limiting water range defines a water content range across which plant growth is less affected by soil aeration, soil matric potential, and soil strength. A wide range indicates that the soil is more resilient to environmental stresses and that plants are likely to be more productive. A narrow range implies the soil is less resilient to environmental stresses and plants growing in this soil are more likely to suffer from water stress, soil mechanical impedance, or poor aeration and are likely to be less productive. More importantly though, LLWR can act as an indicator of the impact of management practices on soil condition. If LLWR is not reduced or is increased it would indicate good management of soil physical properties. A decrease in LLWR might mean that site productivity has been reduced and that forest management is not sustainable. However, the relationship between LLWR and forest productivity has been largely untested. The shoot growth rate of corn (*Zea mays* L.) was correlated with LLWR (da Silva and Kay 1996) and this justifies further studies to determine the relationship between the productivity of forest plantations and LLWR.

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