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Strategies Regarding Approaches to Plant Nutrition and Soil Fertility, Post Drought

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ABSTRACT

Drought is a regular visitor to many countries, including South Africa and Australia. These periods of below-average precipitation have adverse social and economic consequences, increasing in severity as drought conditions persist for months and years. Growers must be vigilant and willing to adapt their usual farming practices during and immediately following these times to ensure a successful future. Actions must be regional, crop and site specific, and well informed from international and local research and experience. Much necessary knowledge that affects fertilizer choice and the factors that influence application-rate adjustments following drought are outlined. Also covered are diagnostic indicators of current soil fertility, both local and international. There is an underlying assumption that hazards due to 'traditional' acid-soil infertility will be dealt with as part of normal farming practices. Five key, post-drought strategies are discussed as exceptions to informed farm management practices during periods of 'normal' rainfall. These exceptions focus on crop and varietal choice for drought tolerance; suggested pre-plant, deep placement of P and K fertilizers prior to rainfall; fine-tuning for tolerance or dependency of crops to vesicular-arbuscular mycorrhizae (VAM); adjustments to usual fertilizer rates, timings and placements for four main reasons; and vigilance for possible sulphide oxidation and consequential acidification. There is a case to reconsider the strong reliance in South Africa on Bray 1 as a diagnostic indicator of soil P status, due to expected wide variations in inter-laboratory measurements. It would also help to strengthen wider use beyond the sugar industry of a routine soil test or tests for soluble silicates and another for P Buffer Index (PBI), the latter to numerically assess soil P fixation to better manage its consequences. Conclusions focus attention on implementation of the identified exceptions post drought. Use of pre-plant, deep placement of starter fertilizers is reliant on access to suitable farming equipment.

INTRODUCTION

South Africa has a land surface of 1 219 602 km^2 of which 12% is utilised for crop production (Anon 2015a, b). The country has an average annual rainfall of 464 mm but with distributions ranging from well below 200 mm annually in the West up to 1 000 mm on the East Coast. This precipitation is low when contrasted with the world annual average of ~860 mm. Farming practices across South Africa cope with limited water, supported with irrigation across some 1.3 million hectares (Anon 2015b; Backeberg and Viljoen 2003; Hassan and Backeberg 2010).

Despite impressive rural-production successes, exceptional circumstances such as fires, floods and drought sporadically confront the land manager and the wider population. Severe, extended drought across much of South Africa, perhaps the worst across the past century of reoccurring droughts of varying spatial and temporal dimensions (Anon 2005), is a recent exceptional circumstance. Global indicators of the 2015-2016 drought in several countries were El Niño climatic conditions, above-average sea surface temperatures across the Southern Hemisphere (still present in April 2016), and lengthy periods of strong negativity in the Southern Oscillation Index that only in May 2016 averaged a small positive value (BOM 2016), suggestive of conditions for drought abatement.

Key Words: cropping, drought, erosion, fertilizers, soil properties, soil testing, strategies, VAM, varieties.

The government of South Africa and others have responded by developing and documenting drought management policies and strategies particularly to deal with agricultural and hydrological droughts that simultaneously cause adverse economic and social impacts across wide areas (Hassan and Backeberg 2010). Expectations and policies nowadays emphasize a need for land managers to adopt proactive approaches focused on risk reduction rather than reactive, monetary drought relief, which is also the approach now adopted in Australia.

Factors documented (e.g., Backeberg and Viljoen 2003) as essential to consider for effective drought management across the agricultural sector in South Africa include social, institutional, cultural, religious, economic, environmental, hydrologic, geographic, educational and political 'instruments'. In contrast, the approach offered to guide drought management on Queensland (Australia) dairy farms (Anon 2013), is more specific. It advises on: know when to act; homegrown feed; purchased feed; nutritive value of feeds; ration formulation, intake and production; and feed budgeting and herd management. It mentions the need (while affected by drought) to 'be ready to fertilise if a rain event is likely', yet few publications advise in detail on farm nutrient management following drought. The few that do focus mainly on assessing residual nutrient reserves and revising recommendations for or following dry weather (e.g., Fall 2012; Mullins and Donohue 2002; Extension Australia 2016). Occasionally (e.g., Mathews 2016), there are warnings on risks that fertilization during a sustained drought can create stressful growing conditions for crops like maize. For sugarcane, the South African Sugarcane Research Institute (SASRI) have a comprehensive set of guidelines for growers to manage their droughted sugarcane that includes savings in growers' fertilizer programs (Anon 2003a).

This paper addresses knowledge and advice for drought recovery by providing relevant explanations, information and strategies pertaining to nutrient management and fertilizer use, supported by international and local experience.

BACKGROUND

Common sense and arbitrary judgements will always be necessary to deal with farm nutrient management post-drought. However, risks associated with inappropriate decisions can be lessened by the application of knowledge accumulated across decades. The challenge is to take a systematic approach that seeks to optimize proposed land uses with contemporary land conditions, including the soil's fertility and moisture status, crop choice, fertilizer management and the like.

Soils

Southern Africa has 29 widely varying soil groups (see Figure 1, adapted from the World Reference Base for Soils). Locally, Fey (2010) has clustered these into 14 groups and then provides, for each group: (i) maps showing their distribution and abundance throughout South Africa; (ii) descriptions of morphological, chemical and physical properties; (iii) correlations with international soil classification systems; (iv) appraisal of soil quality from a land use perspective; and (v) illustrative examples of soil profiles with analytical data and accompanying interpretations, etc. From all of this information, it is certain that soils in rural areas will behave in different ways before, during and following drought. Ultimately, farming practices following drought must integrate the strengths and weaknesses of local soils under prevailing climatic conditions. For example, there is Australian experience in the 'recovery' year to perhaps use two-thirds normal rate of fertilizer P on non-calcareous soils (following crops yielding more than 0.5t/ha or which had healthy growth) and near normal rates on calcareous soils under otherwise similar conditions (Extension Australia 2016).

Producers should know (or get to know) the major soil types on their farms and in particular whether or not these are:

- free draining throughout or poorly drained or often waterlogged, etc.;
- naturally fertile, or have become so via applications of fertilizers, amendments and/or applications of manures and crop residues;
- acidic, neutral or alkaline in reaction at the surface and/or at depth;
- able to retain basic cations in significant quantities on cation exchange sites, as indicated by soil CEC levels above 5-10 cmol (i^+)/kg (e.g., Chernozems, Vertisols);
- low CEC, with low base saturation and plenty of free or active aluminium in the root zone, conditions typically associated with highly weathered soils (e.g., Alisols and others);
- salt and/or sodium affected (e.g., Solonchaks, Solonetzs); and
- known to strongly ‘fix’ soil P in forms not readily available to plants (e.g., Ferralsols, Plinthosols, and others with accumulation of metal oxides, particularly of iron and aluminium).

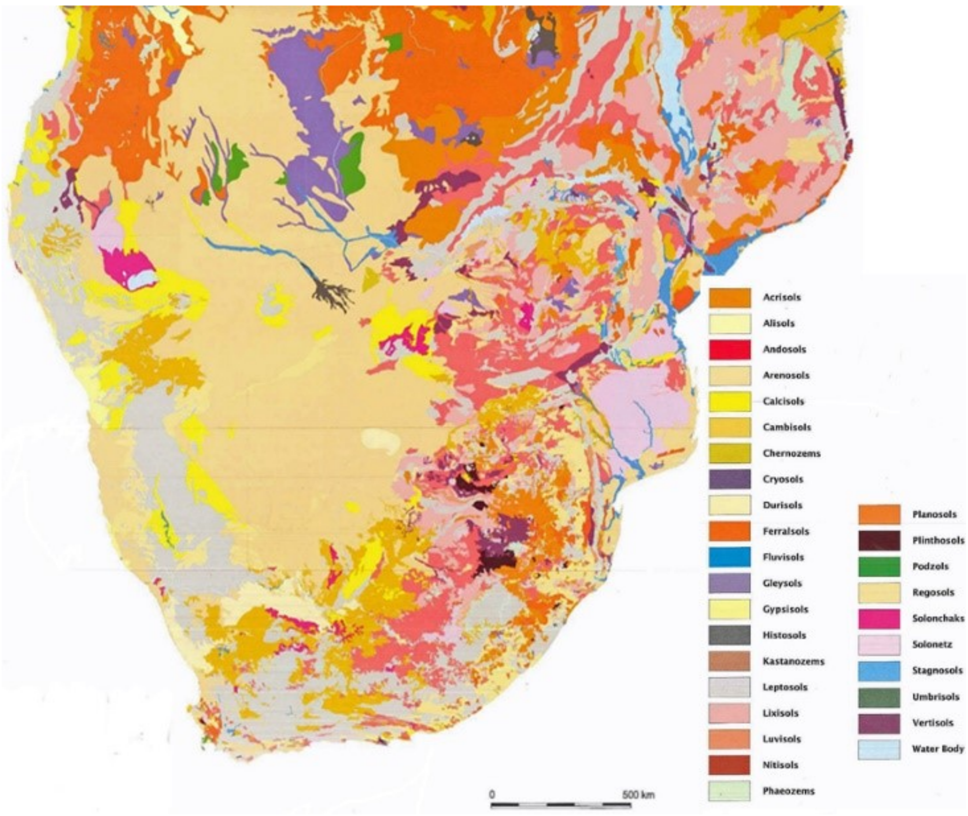

Figure 1. Map of major soils of South Africa, adapted from Soil Atlas of Africa, World Reference Base. http://www.fao.org/soils-portal/soil-survey/soil-classification/world-reference-base/en/.

Soil capability classifications, such as those developed for acidic soils by Sanchez *et al*. (1982) and Myers and De Pauw (1995), can further assist, with selected details provided in Table 1, noting that when expressed as cmol (i^+)/kg, CEC values of >40 rate as very high, values of 15-25 are medium (typical of many fertile soils), while values ≤4 are low, indicative of highly weathered soils with few exchangeable bases (Ca^{++}, Mg^{++}, K^+, Na^+, NH_4^+)[1].

[1] CEC is the acronym for Cation exchange capacity (method affects apparent result), while ECEC is the acronym for ‘Effective CEC’, which (in Australia) is usually the sum of the exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+, K^+; method optional) plus exchange acidity (Al^{3+} plus H^+) from 1M KCl extract. Locally, may equate to ECEC = (CEC - titratable acidity).

It adds to farm management complexity that clay minerals in soils possess both permanent and variable surface charges (the latter both negative and positive). In particular, strong weathering of soils under warm, humid conditions results in the decomposition of predominantly permanent, negatively charged minerals such as montmorillonite. Over the long-term, affected soils often become dominated by variable charge minerals (and organic colloids with similar surface-charge properties), with consequential effects on CECs and anion exchange capacities (AECs). With associated soil acidification, the 'effective' CEC (ECEC) of weathered soils will naturally decline, while soil AEC usually increases slightly. Leaching losses of nutrient cations such as NH_4, K, Ca, and Mg (including those added as fertilizers and amendments) are greatest when soil CECs are ≤4 cmol (i^+)/kg. In contrast, losses of these same nutrients from soils with high to very high CEC values are mostly insignificant, even when there is adequate water and good internal drainage.

As a handy hint, an indication of whether or not a soil could have a net positive surface charge (such soils favour surface retention of anions such as sulfate and nitrate) can be obtained by measuring soil pH in both a 1:5 (or 1:2.5) soil/water suspension and in a 1M KCl extract at the same soil/solution ratio. If delta pH, [pH (KCl) - pH (water)] is zero or positive, the soil is probably dominated by variable charge colloids, including some with positive surface charges (Uehara and Gillman 1980). Also, many of the methods used to measure soil CEC over-estimate this soil property because extracting solutions are chemically too strong (relative to soil-solution ionic strength) and/or artificially elevate natural soil pH to neutral or above (Gillman *et al*. 1982).

Table 1. Information from capability classifications for acidic soils developed by Sanchez *et al*. (1982), Myers and De Pauw (1995) and the author.

Likely soil constraint	***Diagnostic feature/s***	***Management & cropping implications***
Moderately acidic root zone	10-60% Al-saturation of ECEC within 50-60 cm of soil surface, with pH (1:5 soil/water) of about 5.0-6.0.	Lime soil to lower %Al saturation prior to growing Al-sensitive crops and pastures. Be alert for Ca deficiency at depth.
Suspect Al toxicity	Typically, >60-80% Al saturation of ECEC, within 50 cm of soil surface, combined with pH of <5.0 (or <4.7 in soils with elevated organic matter). *[These soils may also be Ca deficient.]*	Plants sensitive to Al toxicity need to be limed, with little root growth and extraction of soil water likely below depth of liming.
Low CEC (or ECEC)	Most important when within the plough layer or surface 20 cm, whichever is the shallower. *Low ECEC definition is ≤4 cmol (i+)/kg.*	Low ability to retain nutrient cations against leaching. This capacity further reduced if soils continue to acidify. Lessen likely losses by splitting N and K dressings and avoid over-liming.
High P fixation, often by reactive Fe.	Particularly applies to plough layer (to 20 cm). Soils often contain kaolinite and Fe and Al oxides, are coloured red (hues of 7.5YR or redder) and have granular structure.	Commonly require high application rates of P fertilizer, as expect little release of P already 'fixed'. Off-site losses of eroded soil can contain elevated total P levels.
Low soil K reserves	Little total soil K and/or exch K <0.2 cmol (i+)/kg and/or low total K/exch K ratio of around <2‒3 (Rayment 2013), and/or few clay minerals containing K in fine fractions of the soil.	For crops with high K demand (e.g. sugarcane), regular inputs of K fertilizer will be required, since many soils have limited ability to replenish removal from their total K reserves.

In custom-made soils such as those used for golf putting greens (Rayment and Baker 1996), plant growth is favoured when these are constructed to 'perch' the water-table, thus retaining moisture and soluble nutrients (N and K in particular) in the active root zone. This is despite a combined coarse and fine sand percentage of around 95%. In the absence of a physical discontinuity between the root-zone and a much coarser sub-grade, the otherwise-identical root-zone will regularly leach soluble nutrients away from plant roots and will also require more rainfall or irrigation water to prevent the rapid onset of drought-like conditions. An example of such effects on turf growth on a lawn bowling green is shown in Figure 2. Particle size discontinuities in natural soils often have the same effect, except that soils grouped as Stagnosols (unlike Planosols) are frequently surface saturated for reasons that do not result from an abrupt textural change.

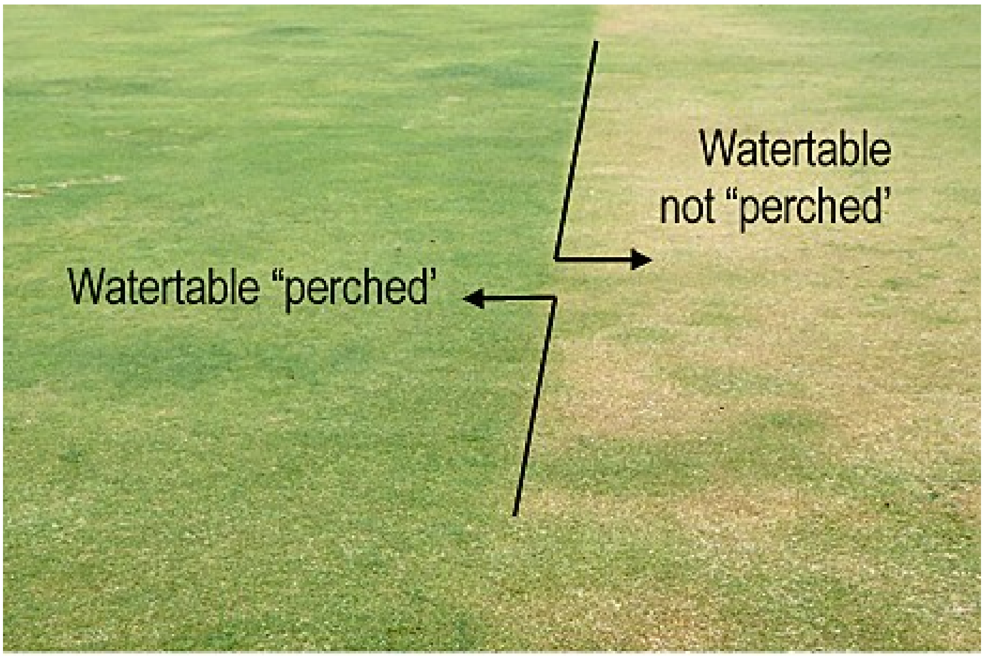

Figure 2. Differences in growth and colour of Tifdwarf Bermudagrass supplied with equal amounts of water and fertilizer growing in custom-made soil with similar chemical and physical properties but with (LHS) and without (RHS) a 'perched' water-table root-zone.

Surface Soils (erosion and biology)

After prolonged drought, vegetation cover that usually protects soil from raindrop-splash and surface-water flow erosion following heavy rainfall is often lacking. Furthermore, vegetative ground cover from zero to 25-30% correlates positively with high soil erosion risk (e.g., Ciesiolka 1987; Rayment and Neil 1997). Surface soils most affected by raindrop-splash erosion are those dominated by fine sands and silt. Soils with coarse surface particles are less affected due to the greater size and weight of those particles.

Strong cohesive forces of aggregates in clay and clay loam soils provide protection from raindrop-splash erosion. However, surface layers of soils with clay and clay loam textures are frequently disrupted, splashed, shifted, and packed together tightly, resulting in surface crusts that lessen air and water entry into the profile. The consequence following heavy rain is increased overland flow with the power to carry soil particles (and nutrients) off-site (Donahue *et.al.* 1983).

Farm managers with weather-beaten soils should, following the onset of drought-breaking rains, make allowance for nutrients lost or relocated by water-driven erosion and perhaps by wind erosion during long periods of drought. Conservative estimates of annual erosive losses of nutrients, supported by grain-cropping data from sub-tropical Australia (Dalal and Probert 1997), are around 10 kg N/ha, less for P, and variable for K due to differences in soil total K reserves. Such losses require consideration when developing nutrient management recommendations.

Another consequence of the prolonged absence of crop residues and weeds due to drought (or from deliberate long-fallowing) is a major decline in populations of beneficial vesicular-arbuscular mycorrhizae (VAM; see Figure 2), which require access to the roots of living plants to survive and reproduce. Consequentially, crops with rooting systems dependent of mutual associations with VAM will require higher fertilizer application rates to offset the absence or low incidence of VAM. The nutrients most affected are P and Zn, but can include Cu and other macro- and micro-nutrients (Jamal *et al.* 2004). Therefore, crops highly dependent on associations with VAM (see Table 2) will be slower to develop, lower yielding or both, unless compensated with the nutrients they are unable to adequately access as seedlings and/or young plants.

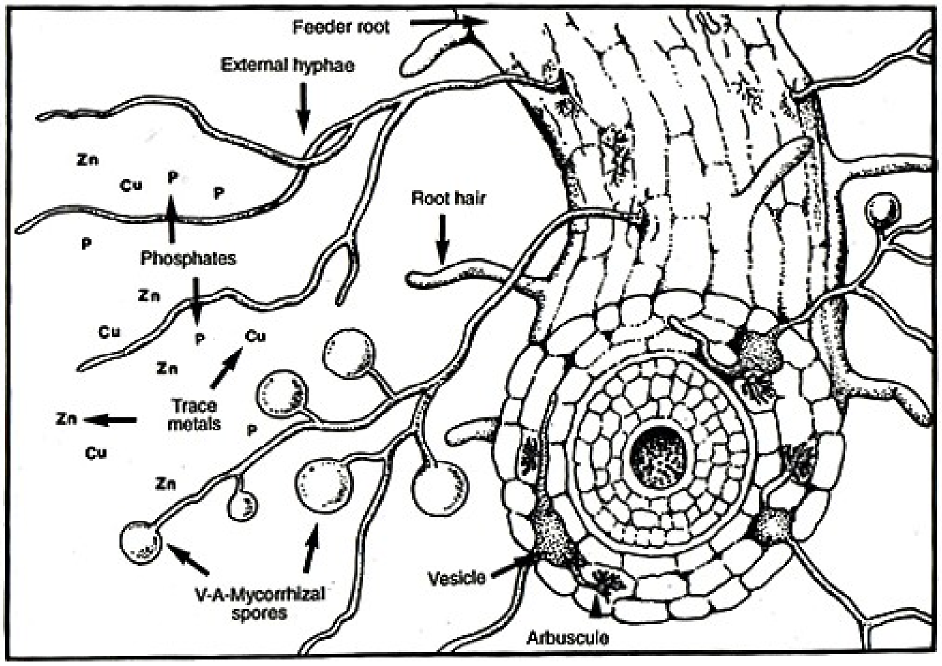

Figure 3. Structure and appearance of microscopic VAM and active root hairs. Hyphae that protrude enhance the absorption of nutrients, especially P and Zn [from Wildermuth *et al.* (1997)].

Present Soil Fertility

Mindfulness of present soil fertility gained from awareness of on-farm soil types is helpful but insufficient. Also valuable but insufficient is access to farm records on production trends, past inputs of fertilizers and amendments, historical soil analyses, and the quantum of nutrients removed in harvested produce. Unused yet still labile nutrients in drought-affected soils, plus nutrient transformations caused by the drying of soils with often concurrent heating, are variables best assessed by reliable soil testing prior to planting or prior to planned fertilizer applications to perennial plants. It is already known from international soil testing experience that chemical changes due to soil drying can affect soil properties in expected ways (Table 3).

Table 2. Examples of the extent of mycorrhizae dependencies, categorised as expected reductions in harvest yield in the absence of VAM on productive crops in cereal growing soils [adapted from Wildermuth *et al.* (1997) and Anon (2002; 2003b; 2016a)].

Dependency category	Likely % yield loss without VAM	Crop type
Very high	>90 - 80	Cotton, Faba bean, Lablab, Linseed, Maize, Pigeonpea
Medium to high	40 - <80	Chickpea, Mungbean, Navy bean, Sorghum, Sugarcane, Soybean, Sudan grass, Sunflower
Low	10 - <40	Field peas, Barley, Oats, Triticale, Wheat
Very low	0 - <10	Canary seed, Panicum
Nil (non-hosts)	0	Canola / rapeseed, Lupins

Table 3. Examples of the effects of soil drying on soil properties [from Etchevers (1986) and Rayment (1993)].

Soil nutrient or soil property	*Expected effects following soil drying*
Ammonium N	Increases or decreases possible.
Flocculation	Generally, more rapid.
Iron	If from an inundated area, concentrations decrease.
Manganese	* If from an inundated area, concentrations likely to decrease. * If soil was aerobic, concentrations likely to increase.
Nitrate	Probable increase.
Nitrite	Decreases or lost.
Potassium	May be liberated to increase concentration or fixed, resulting in a lower concentration, depending on soil mineral composition.
Soil pH	Increases are possible but more likely to become more acidic, especially if sulphide ions are able to oxidise.
Sulfate	Increase expected when soils contain organic sulfur and/or free sulfide ions: for example, acid-sulfate soils (ASS).

Key issues are when and how to soil sample, and the test methods most appropriate in the circumstances. For example, soil chemical properties do change following fertilisation, noting that reaction products from superphosphate application will include brushite [$CaHPO_4.2H_2O$], monetite [$CaHPO_4$], calcium ferric phosphate [$H_4CaFe_2(PO_4)_4.8H_2O$], potassium taranakite [$H_6K_3Al_5(PO_4)_8.18H_2O$], ammonium taranakite [$H_6(NH_4)_3Al_5(PO_4)_8.18H_2O$], calcium aluminium phosphate [$HCaAl(PO_4)_2.6H_2O$]), strengite [$FePO_4$ $2H_2O$] plus amorphous $FePO_4$ nH_2O and amorphous $AlPO_4$ nH_2O (Martin 1963). Of these, it is known (Jan Meyer, personal communication) that the reaction product $AlPO_4$ nH_2O is 40 – 50% as effective as superphosphate as a P source for sugarcane. This finding helped justify use of sulfuric acid-based extractants such as Truog on soils used to assess P sufficiency for sugarcane, since the extractant better relates to “quantity” than “intensity” of plant-available P.

That said, soil P test results from representative samples obtained from the root zone of the proposed crop or pasture are usually sufficient to guide P fertilizer needs. Any off-site losses or gains in soil P from surface erosion (prior to sampling) should be reflected in the soil P result. Common soil sampling depths are 0-10 cm, 0-15 cm or 0-20 or 0-25 cm, the last two applicable to plant-crop sugarcane in Australia (Rayment and Lyons 2011). For mangoes, local samplings of topsoils to 30 cm and from 30 - 60 cm for sub-soils are recommended (Anon 2000).

Soil samples collected to assess the need for P fertilisers are also applicable to use when testing for K and Zn sufficiency. And it is also appropriate (and recommended) to undertake a selection of other soil tests to check on further soil properties that might have changed due to drought and/or drought-breaking rainfall. For example, the use of marginal ground and surface waters for irrigation during the drought may have caused the accumulation of undesirable soluble salts (particularly sodium chloride), with adverse effects on subsequent salt-sensitive crops such as tobacco, clovers, lupins, faba beans and oats. Chloride ions also facilitate cadmium uptake by crops such as potatoes across a range of soil pH values, noting that cadmium is a toxic heavy metal that commonly enters plant and animal food chains (Bureau of Resource Sciences 1997; Warne *et al*. 2007).

Appropriate soil tests for use following drought usually default to selections from those offered routinely by local soil testing services, which may not always be the best available internationally. Indeed, local laboratories mostly offer methodologies and fertilizer-use calibrations developed several decades ago. Nowadays, a typical suite of soil test methods available in South Africa to inform fertilizer- and amendment-use decisions are summarised in Appendix 1, along with a comparative suite of soil tests routinely available from commercial services in Australia. Strong focus on the Bray-1 soil test for extractable P in South Africia is a surprise, given its proven poor inter-laboratory measurement quality across Australasia since 1992-93 (e.g., Rayment *et al.* 2007) for all likely Bray-1 test levels. Local use of 0.1M HCl as the main extractant for micronutrients such as Zn and Cu is also a surprise, based on soil testing experience from Australia for crops other than sugarcane.

While not mentioned in the AgriLASA Soil Handbook (2004), it is understood (Jan Meyer, personal communication) that a diagnostic test for soluble silicates, based on extraction with 0.01M $CaCl_2$ (Berthelsen *et al.* 2001) is used on South African canelands. The diagnostic test for soluble silicates more commonly preferred for Queensland’s acidic, weathered cane-growing soils, where as many as 30% are yield-responsive to applications of soluble silicate, is based on overnight equilibration with 0.005M sulfuric acid (e.g., Haysom and Chapman 1975; Haysom and Kingston 1999). The critical range separating response from non-response in Queensland is around 89–120 mg Si/kg (Kingston 1999).

An important omission from Appendix 1 for South Africa is a test that directly estimates soil P buffering capacity (e.g., PBI), although there is local use of a phosphate desorption index (PDI). PBI tests are now in commonplace use, particularly across eastern and southern areas of Australia. Moreover, the PBI test was endorsed by the Australasian Soil and Plant Analysis Council Inc (ASPAC) in 2001 and is nowadays mandated in regulations that guide P fertilizer recommendations for plant-crop sugarcane in ‘reef catchments’ of eastern Queensland (Dept. of Env. and Heritage Protection 2016).

As a general guide, the P buffering capacity of Vertisols (or similar deep cracking clays), as represented by PBI values, are intermediate between podosols and sandy soils (these generally have low P-fixation properties), and the Ferralsols (and similar soils that are high P ‘fixers’). Moreover, PBI values <15 rate as extremely low, those between 70-140 rate as low, those from 140-280 rate as moderate, while values ≥840 rate as very high in their ability to fix fertilizer P. When soil P ‘critical values’ are known to be influenced by soil P fixation status, they may warrant downwards adjustment when PBI (or a similar index value) is low, and upwards movement when expected P sorption is high to very high. There are similar experimental findings for high P-fixing Ferrasols in Kaw Zulu Natal Midlands (Jan Meyer, personal communication). Specifically, topsoil Truog-P status combined with PDI was better correlated to the P requirements of local sugarcane than was the Truog-P test alone.

Ideally, the land manager, particularly those intending to sow grains and other field crops, should also assess sub-soil fertility and moisture status to 60 or 90 cm, or to the expected crop rooting depth. The sub-soil testing focus would be on nitrate (or nitrate + ammonium-N), sulfate, soil acidity, plus salinity and sodicity, the latter two when soil types and topography dictate. Starter N fertilizer will likely be required for potentially high-yielding cereal and other grain crops when nitrate-N levels in surface horizons test very low to low but ‘bludge’ at depths around 60-90 cm and deeper.

Additional guidance on ‘potential’ soil N mineralization is sometimes derived from tests such as organic C (OC). Indeed, OC (Walkley and Black’s method) is included as a regulated soil test for plant-crop canelands in ‘reef catchments’ of eastern Queensland (Dept. of Env. and Heritage Protection 2016) as a guide to six soil N mineralization classes.

The superior option used in Southern Africa is to directly estimate soil N mineralization from recently-sampled soils, particularly following drought-breaking rains when many cane-growing soils exhibit above usual amounts of N mineralization (Anon 2003a). Near infra-red spectroscopy is then used when performing the tests routinely in the laboratory. With a low soil mineralization rating, local advice is to reduce usual fertilizer N recommendations for rainfed sugarcane by 20 kg N/ha. As soil mineralization ratings increase to Category II (medium), the recommended reduction is 30 kg N/ha. Corresponding reductions are 40 kg N/ha for soils with a high rating, and around 50 kg N/ha for Category IV soils with a very high N mineralizing status (Anon 2003a).

When contemporary soil tests (and perhaps plant analyses) are lacking, the land manager should utilise local district recommendations, but with caveats. For example, and particularly on soils that don’t strongly fix P, expect there to be a small increase in levels of plant-available P following drought, when earlier inputs probably exceeded removal by affected crops. Additionally, in fertilised fields that failed to produce a mature crop due to drought, soil mineral N (particularly nitrate-N) status would likely exceed usual pre-plant levels, provided what did grow was not grazed or removed for hay (Mullins and Donohue 2002). Mineralisation of soil and fertilizer N would have continued slowly under drought conditions and would be expected to quickly increase following drought abatement and soil-N mineralization until utilised by seedlings or by early pasture growth.

STRATEGIES FOR FERTILIZER CHOICE, RATE & PLACEMENTS POST DROUGHT

Fertilizer choice and management post drought has much in common with farming practices employed at other times, with five important exceptions. Assuming any usual soil acidity and/or soil physical constraints are absent or have been adequately dealt with, these five are:-

(a) Give preference to drought tolerant crops and/or drought-resistant varieties *[if available and when it is unclear if drought conditions have fully abated]*;

(b) Consider pre-plant, deep placement of starter fertilizers prior to seasonal and/or expected drought breaking rains;

(c) Fine-tune for VAM tolerance or dependency of proposed crops;

(d) Adjust usual fertilizer application rates and timings to account for: (i) soil fertility status (ii) surface-soil erosion between soil testing and sowing time; (iii) current soil moisture status; (iv) early or delayed sowing times; and (iv) absence of 'perched' water-tables in root-zones, particularly of sandy-loam topsoils; and

(e) Remain alert for unexpected circumstances.

Drought Tolerant Crops / Varieties

Pearl millet is perhaps the most drought-tolerant of all major staples (Anon 2016b). Selected varieties of grain sorghum also exhibit impressive tolerance to drought conditions. Also, early maturation is often an advantage in times of drought or late-season sowings, with 'Okashana 1' millet known to mature around 4-6 weeks earlier than many 'traditional' varieties.

Given that drought is second only to soil infertility as a constraint of maize production, it is fortunate that drought-tolerant cultivars have emerged. There are also drought-tolerant varieties of barley and a range of grain legumes, including cowpeas and pigeonpeas. It follows that an early, on-farm decision is to decide on the crop (or pasture) to be grown and/or fertilised. Crop variety is usually a secondary decision, where choice may range between a known high-yielding variety or an unproven variety recognised for its drought tolerance. Local knowledge of soil moisture reserves and expected seasonal conditions can assist with such decisions.

Pre-plant, Deep Placement of Starter Fertilizers

Based on emerging results from present field research across the semi-arid grain cropping lands of sub-tropical eastern Australia (D. Lester, unpublished data), useful gains (see Figure 3) in wheat growth have been achieved by placing 'starter' P and K fertilizers into the soil as far in advance of sowing the next crop as possible, usually around 15 to 25 cm deep, with a row spacing of 50 cm. In soils with a long cropping history exhibiting soil-fertility decline, N as urea is subsequently applied between the bands at a shallower depth to add to the N contribution from mono-ammonium phosphate, the presently preferred P source.

An important advantage from deep, early placement of P (and K fertilizer if necessary) is that it increases the period between fertilizer application and sowing, allowing for more rainfall events to 'wet-up' the soil profile. Other researchers, including Tandon (1987) and Dibb *et al.* (1990), have reported deep-banding of 'starter P' as a successful strategy for small grain crops in soils prone to drought, although response and profitability are affected by soil P status, P sorption capacity, nutrient balance, soil-water availability and crop type (Hedley *et al.* 1995). Interaction of N, P and K are of special significance, often determining whether responses to P additions occur and the extent to which they are beneficial and profitable.

Figure 3. Responses by wheat to the presence (foreground) and absence (centre rear) of deep (15 to 25 cm), pre-plant P fertilizer on the semi-arid Darling Downs of Queensland (photograph courtesy of D. Lester)**.**

Fine-tune for VAM Tolerance or Dependency

One strategy is to select crops with low or very low VAM dependency (see Table 2). Canola is an example. Such crops will not suffer yield loss following drought with usual fertilizer application rates but will still increase VAM inoculum for following crops.

For crops highly reliant on VAM associations such as cotton, sugarcane, sunflowers and maize, however, higher than usual rates of P and Zn fertilizers should be seriously considered when sowing or planting into paddocks with bare-fallows of several months' duration, irrespective of the reason but inclusive of drought (e.g., Thompson 1987). This practice should continue until VAM have had time to spore and re-populate in previously drought-affected fields. Alternatively, there can be benefits after 14 - 28 days following inoculation of bare fields with VAM propagules, such as infected root fragments and/or VAM spores (Bellgard 1992; Anon 2002). Usually one crop-cycle is sufficient for natural 'recovery'. Also, VAM dependency varies with soil P fertility. It is highest when sensitive crops are sown into soils with low extractable P status and less so (~50% of possible sensitivity) at moderate levels of plant-available soil P. For sugarcane, the soil P level separating responsive from non-responsive locations is reported to increase by a similar percentage when paddocks lack effective mycorrhizal propagules (Anon 2002).

Other Fertilizer-Rate Adjustments

There are four persuasive reasons for upwards or downwards adjustments to fertilizer rates initially based on soil test results obtained prior to drought-breaking rainfall and usual on-farm experience. Ultimately, however, recommendations on forms, rates, methods and timings of applications are variables best supported by local experience across multiple years and soil types. For example, P use efficiency is enhanced when the fertilizer is placed in or in close proximity to crop roots to encourage speedy contact and also to lower the portion fixed by soil, particularly when the fertilizer has a low salt index, noting effectiveness and efficiency will be less or lost if N and other essential plant nutrients are lacking.

Firstly, there is need to make upwards adjustments to fertilizer rates when fine and/or light soil fractions are known to have been lost from the paddock by surface erosion. Assuming soil losses of 1 - 2 tonnes/ha, consider increasing nutrient inputs for crops such as maize and wheat by about 10, 2 and 5 kg/ha of N, P and K, respectively. Alternatively, resample and retest the soil and use those results to guide actual application rates in conjunction with local soil test interpretative criteria. When paddocks have accrued soil eroded from elsewhere, corresponding reductions in fertilizer applications may be feasible.

Secondly, upwards or downwards adjustments to normally-recommended application rates of N may be warranted, guided by the pre-sowing depth estimates of moist soil, obtained with a soil-moisture meter or a simple probe. Examples for Vertisols and similar soils from semi-arid cropping lands on the Darling Downs of Queensland (Australia) are provided as a guide in Table 5.

Table 5. Guidelines (Anon 1970) for Vertisols and similar soils under semi-arid Queensland conditions to adjust usual N fertilizer application rates for wheat at different pre-plant levels of nitrate-N to 60 cm and pre-plant soil moisture depths for a mid-season planting. See table notes for adjustments to account for earlier and later sowing dates.

Soil nitrate-N rating to 60 cm	*Depth (cm) of soil moisture*	*Approx. change to N fertilizer recommendation at mid-season planting times*
Very low	120	+ 20%
	90	+ 10%
	60	+ 5%
	30	No adjustment
Low to medium	120	+ 40%
	90	+ 30%
	60	No adjustment
	30	0.6 % times usual rate
Medium to high	120	+ 25%
	90	No adjustment
	60	0.7 times usual rate
	30	0.6 times usual rate
High to very high	120	No adjustment
	90	0.3 times usual rate
	60	No fertilizer N recommended
	30	No fertilizer N recommended

Notes: *Planting date adjustments for wheat under semi-arid conditions:*

- For late autumn-early winter plantings, increase N rate by 10% and use normal seeding rates.
- For later-winter plantings, use 80% of usual N rate and 25% higher seeding rate (to account for less-than-normal tillering).
- For very-late plantings, use 50% of usual N rate and 50% higher seeding rate (due to little expected tillering).

Thirdly, typically, soil P 'critical values' and fertilizer P rates warrant downwards adjustment when PBI values (or equivalent) are very low. They deserve upwards adjustments of up to four fold for wheat when intended for soils with very high PBI ratings. Upwards adjustments, however, can be as much as seven to eight fold for potatoes, which have a high internal P requirement.

Fourthly, growers should make assessments of rooting zones across their main paddocks and soil types for evidence or otherwise of water-table 'perching'. If there is no obvious 'perching', the best strategy when fertilizing with N and K, is to favour small and frequent inputs to help retain these key nutrients where there are active roots, which concurrently assists in minimising possible nutrient losses by leaching. In addition, these areas typically benefit from small, regular applications of irrigation water.

Unplanned Consequences

Whether derived from sulfidic mine wastes at any landscape location or from pyritic minerals in actual and/or potential acid-sulfate soils (ASS), the latter commonly located in low-lying land systems relative to coastal mean height datum, sulphide ions and minerals such as jarosite can oxidise when the soils in which they occur are subjected to oxidation (Gardner *et al.* 2002). This is possible following extended periods of drought and when ground-water tables have lowered.

In addition to strong acidity, the partial oxidation of pyrite commonly produces jarosite (Equation 1), an easily recognised, pale yellow-coloured mineral often seen in ASS affected areas. Under favourable conditions of on-going oxidation and moisture (after drought abatement) jarosite can be decomposed by hydrolysis (which does not require further atmospheric O_2) releasing additional strong acidity and iron (as geothite) into the environment. That reaction is represented by Equation 2.

$$FeS_2 + 15/4\ O_2 + 5/2\ H_2O + 1/3\ K^+ \rightarrow \underset{\text{jarosite}}{1/3\ KFe_3(SO_4)_2(OH)_6} + \underset{\text{sulfuric acid}}{3H^+\quad 4/3\ SO_4^{2-}} \quad \text{---(1)}$$

$$\underset{\text{jarosite}}{KFe_3(SO_4)_2(OH)_6} \xrightarrow{H_2O} \underset{\text{geothite}}{3\ FeO.OH} + K^+ + 3\ H^+ + SO_4^{2-} \quad \text{---(2)}$$

In the final stages of oxidation, the Fe^{2+} liberated in reactions such as that shown in Equation 3 is water-soluble and can be transported considerable distances away from the initial source of pyrite or sulphide ions and often into nearby streams.

$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + \underset{\text{sulfuric acid}}{16\ H^+ + 2\ SO_4^{2-}} \quad \text{---(3)}$$

In these waters (or even within the soil profile), oxidation of Fe^{2+} can produce characteristic red brown flocs of FeO.OH, with further releases of strong acid. This is termed 'acid at distance' (Equation 4.; Gardner *et al.* 2002).

$$Fe^{2+} + ¼\ O_2 + 3/2\ H_2O \rightarrow \underset{\text{geothite}}{FeO.OH} + 2H^+ \quad \text{---(4)}$$

Best management approach, which is valid prior to, during, or following drought, is to eliminate the threat or confirm the risk of oxidation of sulphide ions and/or the presence of actual or potential ASS using proven methods of analysis documented in Rayment and Lyons (2011). This book also includes laboratory and field methods to estimate the quantities of amendments (typically limestone) required to neutralise actual and potential acidification hazards. Fey (2010) mentions the existence of such soils in South Africa, and while a fairly new phenomenon for the sugar industry in Southern Africa, such soils are known to occur along the Mozambique Coast, extending to Tanzania (Jan Meyer, personal communication).

CONCLUSIONS

There are a plethora of strategies and approaches related to plant nutrition, soil fertility and rural productivity that can and should be considered by farmers and their advisers as they emerge from drought. A requirement is to know the properties of affected soils and landscapes in conjunction with usual crop (or pasture) management practices including fertilizer recommendations. What is then required is to integrate these with a series of important exceptions explained and documented herein. Some of these exceptions are visible or easily ascertained, such as whether or not it is appropriate to select drought-tolerant varieties and species that may be lower yielding or less profitable than 'traditional' options.

An important step is to undertake or commission diagnostic soil tests before or following drought-breaking rain to provide initial guidance on present land suitability and nutrient status on a site-specific basis. Moreover, those tests should be as comprehensive as possible, but will be constrained by what is offered by local or regional soil testing services. Based on the information collated in Appendix 1, the present 'suite' of commercial soil tests marketed in South Africa could be enlarged to particularly embrace a direct measure of soil P fixation status; e.g., PBI. Local preference for the Bray-1 test as a diagnostic measure of soil P status is also questioned, largely because documented Australasian experience since the early 1990s suggests it suffers from poor between-laboratory measurement quality. Indeed, numeric differences in reported values can easily overlap those listed in any two or so of the six soil test categories of Bray-1 P listed by Schmidt (2013) for a range of maize target yields in South Africa.

The post-drought strategies documented herein as exceptions, including species or varietal choice, are all reasonably simple to evaluate and implement, albeit the ability to undertake pre-plant, deep placement of starter fertilizers prior to seasonal and/or expected drought breaking rains is reliant on access to suitable farming equipment. Fine-tuning, however, for VAM tolerance or dependency is relatively simple, although it helps to be aware of contemporary soil P and soil Zn fertility-status of the surface root-zone prior to finalizing decisions on crop type and fertilizer use at planting. That said, it is unlikely that recycled organics will meet the immediate nutrient needs (P and Zn) of VAM-sensitive species, following conditions of extended fallow and drought, unless supplemented with those nutrients or by prior inoculation of bare soils with VAM propagules. Adjusting usual fertilizer application rates and timings to account for soil gains and losses due to recent erosive events, for soil moisture status, and for the expected absence of 'perched' water-tables in soil root-zones are all easy to assess and implement. The remaining exception is to be alert for strong acidity on-site or at a distance following the oxidation of sulphides and pyritic minerals due to exceptionally dry conditions only likely to be experienced in areas adjacent to mining and mine-waste containing sulfides, and in low-lying soils derived from Holocene marine sediments deposited during the last 6,000 to 10,000 years when oceans were up to one metre higher than present (Gardner *et al.* 2002).

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Appendix 1.

Commercial soil tests used in South Africa and in f Australia for assessing the fertility status of paddocks typically prior to making fertilizer recommendations. The Australian chemical methods are those of Rayment and Lyons (2011). For South Africa, see AgriLASA Soil Handbook (2004)[†].

Routine soil chemical and physical laboratory tests		Purpose / Comment
South Africa	Australia	
Saturated soil paste extract for high clay soils, then 1:5$_{\text{soil-water}}$ for electrical conductivity	Electrical conductivity, 1:5 soil-water	Measure of soil soluble salts plus ionic strength by calculation.
pH (1:2.5 soil/water and with 1M KCl; also with 0.01 M $CaCl_2$in sugar industry)	pH (1:5 soil-water) and 1:5 0.01 M $CaCl_2$; sometimes with 1M KCl as an alternative to 0.01 M $CaCl_2$.	Estimates of soil acidity / alkalinity.
Conductance of saturation extracts plus soluble cations	Water soluble Cl	In Aussie, contribution of Cl^- to soil soluble salts as a further indicator of soil salinity hazard.
Organic Carbon — W&B	Organic carbon —W&B	A common measure of soil OC, with unreliable measurement agreement between labs. It is a regulated test used when assessing N fertilizer requirements in ‘reef catchments’ of Queensland.
Total C (and TOC) by Leco Carbon Analyzer	Total organic C (several methods)	Alternative to $OC_{W\&B}$.
NO_3^- & NH_4^+ following extraction with 0.1N K_2SO_4	Water soluble nitrate N	Pre-plant N status of cropping soils in particular, typically in surface horizon and separately to 60-90 cm.
Mineralisable N (with NIR measurement)		Calibrated for the sugar Industry since 1990s.
	Colwell extractable P [0.5M $NaHCO_3$ @ pH 8.5 with soil/solution ratio of 1:100 for 16 h]	Most common soil P test for crops and pastures in Australia for both acidic & alkaline soils. There is reasonable measurement agreement between labs. A “P-quantity” estimate with “critical levels” affected by soil P fixation status.
Olsen extractable P	Olsen extractable P [0.5M $NaHCO_3$ @ pH 8.5 with soil/solution ratio of 1:20 for 30 min]	Often used for crops & pastures in southern Australia, with reasonable measurement agreement between Aust labs. In South Africa, used on soils with pH >7 containing free lime. Favours “P-intensity”, with “critical levels” affected by soil P fixation status.
Bray-1 extractable P	Bray-1 extractable P	Limited use in NSW (Aust). Locally preferred by fertilizer industry (Schmidt *et al.* 2007; Schmidt 2013). Bray-1 has had poor between labs’ quality for years across Australasia.
Truog-P and Bray-2 P	Acid extractable P (0.005M H_2SO_4 @ 1:200 for 17 h) [BSES P]	BSES-P has long use on Queensland canelands but with lower measurement quality than P tests other than Bray-1. Truog-P and Bray 2-P have limited uses in South Africa.
‘Resin Bag’ Ext P, and separately with Resin-paper strips	DGT extractable P (Mason *et al.* (2010)	Use of diffusive gradients in thin-films (DGT) has emerging use in southern Australia for cereals and other grains. There is no independent QA data in Australasia for this new P test.

Routine soil chemical and physical laboratory tests		Purpose / Comment
South Africa	**Australia**	
Ambic 1-P (or Ambic 2-P)		Less common than Bray-1 P. Has multi-nutrient uses and preferred by Grain Crops Institute for calibration research (Schmidt *et al.* 2004; Schmidt 2013).
Phosphate Desorption Index (PDI)	P buffer index (with Colwell P) [PBI; R&L Method code 9I2]	PBI used across Australia since 2001 to adapt fertilizer P recommendations to P buffering. *Warrants adoption and use in South Africa*. PDI used at SASRI (ex. Sumner) for rapid, routine screening of soil P-fixing capacity.
0.01M $CaCl_2$ extractable soluble silicate (Berthelsen *et al.* 2001)	Acid-extractable soluble silicate [0.005M H_2SO_4 @ 1:200 for 16 hr; R&L Method code 13D]	Use of 0.01M $CaCl_2$ extraction preferred by local sugar industry; 0.005M H_2SO_4 common on Queensland's weathered soils growing sugarcane to provide a diagnostic estimate of Si deficiency or sufficiency.
S by 1 N Ammonium. Acetate/Acetic acid or with calcium phosphate	Phosphate extractable S	Estimates of plant available SO_4-S.
	KCl 40 Extractable S	Test with increasing popularity for plant available SO_4-S in eastern Australia.
0.1M HCl extractable Fe, Cu, Mn & Zn	DTPA extractable Fe, Cu, Mn & Zn	Estimates of Zn, Mn and Cu for deficiency & toxicity. HCl is unsuitable for strongly alkaline soils. May use Ambic-1 or 2 in South Africa.
Hot water extractable B or dilute, hot $CaCl_2$ extraction	Hot $CaCl_2$ extractable B	For B deficiency and toxicity predictions.
	Exchangeable Ca, Mg, Na, K — 1M NH_4Cl extract	For fertility and as part of estimating soil ECEC.
	Boiling 1.0M nitric acid extractable K	Used in the sugar industry of Queensland for several decades; e.g., Chapman (1971).
Extractable Ca, Mg, Na, K — Am. Acetate – by shaking	Extractable Ca, Mg, Na, K — Am. Acetate – by shaking	In South Africa for cations: quick test for basic cations in Australia.
Exchange acidity with 1M KCl or weight or volume basis	Exchangeable Al and Exch H (Exchange acidity) with 1M KCl – on weight basis	Used in Australia to estimate ECEC and %Al saturation of ECEC. Similar uses in South Africa.
CEC (volume basis)	ECEC (weight basis)	Estimate of soil's ability to hold nutrient cations by cation exchange.
Mehlich-3 extractable B, Ca, Cu, Fe, S, Mg, Mn, P, K, Na & Zn	Mehlich-3 extractable Al, B, Ca, Cu, Fe, S, Mg, Mn, P, K, Na & Zn	Growing number of laboratory users in Australia with measurement quality for P now as good as for Colwell & Olsen P. Mostly for precision Ag in South Africa at this stage (A. van Vuuren, personal communication).
Sand / Silt / Clay; estimates of clay type/s by NIR.	Soil texture and soil colour; estimates of clay type/s by NIR or MIR mostly used for R&D..	Apart from soil texture and colour, soil physical tests not usually measured routinely in Australian diagnostic soil testing laboratories.

† Colour-coding of rows in the tabulation is only to assist with recognition of related soil test groupings.