

IMPORTANCE OF SOIL ORGANIC MATTER IN SOIL HEALTH AND AVOCADO ORCHARD MANAGEMENT

Setting the Scene: Soil Health and the Organic Conundrum

Soils vary widely in composition, as affected by parent material, climate, topography, living organisms, time, and management. The mineral component is usually >90%, with soil organic matter (SOM) comprising 0.1 – 10%. SOM in a typical fertile soil will have a *living* component of about 15%, of which roots comprise 5 – 15% of biomass; soil fauna (nematodes, earthworms, protozoa and microarthropods) 5 – 10%; and micro-organisms (decomposers, N₂ fixing microorganisms, denitrifying microorganisms, mycorrhizae and algae) 75 – 90%. The *non-living* SOM consists of macro-organic matter, humus (70 – 85%) and inert carbon (C) (5 – 20%) (Haynes & Graham, 2004). SOM is a key component of soil health/condition, defining soil fertility, stability, erosion risk, nitrogen (N) and carbon (C) stores, and soil microorganism and soil fauna activity.

This paper summarizes the importance of SOM in “soil health”, and discusses how to maintain SOM content through management, or – at least slow down SOM losses in orchards. Increasing or restoring SOM losses brought about by cultivation, tillage, reduced organic matter inputs and greater losses, is at best a very long-term endeavour. Growers should also at least be aware of SOM stocks on a global basis, and the important C sink role that they can play in sequestering and storing carbon – and therefore helping to reduce atmospheric C (CO₂) build-up and resultant global climate change. The problem is that SOM can also be a net C source to the atmosphere if poorly managed in agriculture.

So-called “organic farming” and “organically produced” farm produce has devoted adherents – both producers and consumers of farm produce. It is stressed that this author is not a proponent of “organic farming” as advocated by “extreme environmental elitists” (as described by 1970 Nobel Peace Prize winner and father of the first Green Revolution, Norman Borlaug). Borlaug (2000) warned that such well-financed anti-technology and anti-science activist groups threatened the potential of biotechnology (including “genetically modified foods”) to adequately feed the about 8.3 billion people in 2025. He reiterated (as many subsequent scientific studies have found) that there is no *credible scientific evidence* to back the false assertions concerning the safety of genetically modified foods (or for that matter that “organically” produced food is safer and more nutritious than responsibly and conventionally produced food using current technology). Edmeades (2012) in New Zealand also warns of the pseudoscience and anti-science threat to agriculture, and discusses why the whole organic farming movement is pseudoscience. He believes that we are in a “Post-modernism” period (as opposed to the prior “Age of Reason” where science was the authority). All too often today “truth” is not revealed by reason based on good evidence, but by “if you believe it is true” – evidence be damned, we have to save the planet!

The aim of this article therefore is to emphasize the importance of SOM in soil health, sustainability of orcharding, and as a means of storing carbon in the soil. It is not a primer on mulching or composting, important as they are. The author has advocated organic matter addition to avocado soils since the early 1980's, as for example in the "Pegg Wheel" integrated management package for *Phytophthora* root rot (PRR) in avocado orchards. The key to this concept, recently revised (Wolstenholme & Sheard, 2010) is that it emphasizes *both* organic matter use, and synthetic chemicals, fertilizers and the best modern technology – hence "integrated" disease management. A totally "organic" farming philosophy for avocados dispenses with "unnatural" human technology, is difficult, and expensive. In the medium term it is bound to fail on moderately heavy soils in wet cycles, when PRR becomes impossible to properly control using pre-1970's technology. In fact, the release of phosphonate "fungicides" in the late 1970's was literally the saviour of the avocado industry in South Africa.

SOM is the grower's friend and there to be treasured and nurtured by good science, but it is only part of the story. The use of modern technology based on good science, as part of a package deal, is sensible, logical and indeed imperative. Oxford University economist Paul Collier writes that the scientifically literate as well as politicians must be educated to counter the populist romantic hostility towards commercial and scientific agriculture (Collier, 2008). As Carl Sagan wrote, the best antidote to pseudoscience is science itself.

A Global View of the Role and Management of Carbon Stored in Soils

By far the largest amounts of carbon in the global carbon cycle are stored (sequestered) in sedimentary rocks such as limestones and dolomites - on ocean floors and on continents. In fact sequestered C in dissolved form, from carbonate (CO_3) and bicarbonate (HCO_3) in the *oceans*, plus that in marine limestone *sediments*, is about 55 times more than all the C stored in earth's atmosphere. It is the steady rise of atmospheric C (CO_2) from human activity since the Industrial Revolution which is of concern (along with other "greenhouse" gases) in climate change. The average residence time of CO_2 is about 3 years in the atmosphere and about 1 500 years in the oceans (Miller, 1998).

Where does C stored in *soils* fit into the picture? It is important to note that the amount of C stored in soils world-wide is more than C stored in *plants*, and in the *atmosphere*. Recent estimates put global soil organic C (SOC) at about 1 500 Pg C. However, estimates vary widely and depend on many factors including soil depth (e.g. there is 1.5 to 2 times more SOC to 3m depth as compared to 1m depth). In fact, soils and surface litter store two to three times as much C in organic form (SOC)

as C in our atmosphere. This SOC comes from decaying vegetation, fungal and bacterial growth, decayed animal remains, and metabolism of living organisms. Scharlemann *et al.* (2014) concluded that about two-thirds of global soil C is in the form of SOC - the rest in inorganic C.

Global soil C stocks, mainly SOC in the form of SOM, are therefore substantial, and very important in our attempts to limit the rise in atmospheric CO₂ concentration - ideally, to contain or reduce it (decarbonize the atmosphere to a level that mitigates climate change). Unfortunately, according to Scharlemann *et al.* (2014) there is consensus that *changes in land use and land cover* (especially deforestation for agriculture) are the second largest anthropogenic source of atmospheric C (after omissions from burning fossil fuels). Land management, especially agriculture affects soil C stocks, and as farmers and orchardists we can and must play our part in conserving SOM.

In over 60% of global land area, SOC comprises most of the total C stock - because of low plant biomass, or highly organic soils. Such areas in particular require management to conserve soil C (and ideally restore native vegetation) (Scharlemann *et al.*, 2014). It is widely known that converting native vegetation to cropland results in an estimated loss of 25 – 50% of SOC.

What management approaches are available to reduce SOC losses in agriculture?

- Manuring and fertilizing to increase crop growth and therefore crop residues
- Zero tillage or conservation tillage
- Cover cropping
- Management of crop residues
- Agroforestry, reforestation & afforestation (Scharlemann *et al.*, 2014).

While not all of the above is practical or directly applicable to orcharding, it is an example of current thinking on climate change mitigation, and will undoubtedly be more thoroughly researched in future. The time may well come when legislation will make SOM conservation imperative.

Coming specifically to SOM conservation in *avocado orchards*, current best practice discourages *soil tillage* (which aggravates Phytophthora root rot), and therefore encourages SOM preservation. *Mulching* of orchards is also widely practiced - not only with avocado prunings, (which have been shown to be excellent mulches after cutting up by a mulching machine), but also other suitable mulches brought into the orchard. The more woody/stalky mulches with higher C:N ratios are decomposed more slowly, but may cause a temporary soil nitrogen drawdown (“negative period”). They can be used when tree vigour is excessive due to high N soils.

Some growers use *composts*, and these certainly promote soil health and SOM conservation. However they are not a panacea, can vary in composition, are expensive, and should (if available) be only part of a fertilization/SOM conservation programme. The same applies to *kraal (cattle) manure*. *Cover cropping* is mostly used prior to orchard establishment, or in newly planted non-bearing orchards.

All the above practices are positive for SOM preservation, and their adoption is only constrained by practicality, availability, or expense. This author is on record that OM addition to avocado soils is in most circumstances beneficial (especially mulching on low SOM soils and in stressful climates). Removal of organic “wastes” (prunings, weed and grass residues etc.) from orchards should be a criminal offense (except for diseased trees with sunblotch viroid or similar transmissible diseases and pests)!

Orchard practices which accelerate SOM decomposition are those which favour decomposition (mineralization) of the more labile component of organic matter. Mineralization results in the release, in plant available form, of plant nutrients, especially nitrogen (N) but also sulphur (S) and others. This should be regarded as “free” N, of which substantial quantities are mineralized each season from soils with humic A horizons. This is of course a loss of SOM, but only a fraction of the total SOM is mineralized each year in high OM soils (see later discussions).

SOM decomposition is favoured by warmth, moisture, tillage, aeration, and by liming. These factors favour the soil microorganisms which use SOM as a food source. Discretion is therefore needed, and certainly tillage is to be discouraged. The key is to make up for the SOM losses by replenishing the stocks with mulches, composts, cover crops (where applicable), as well as by residues from improved plant growth resulting from plant nutrition, and proper spacing and orchard floor management. In all circumstances, OM additions must be tailored to specific orchard conditions, and monitored by scientifically interpreted avocado soil and leaf analysis.

Organic Matter in Avocado Orchard Soils

SOM comes from plant and animal (including micro-organism) remains in various stages of decomposition, eventually stabilizing as humus, closely associated with clay particles (Handreck & Black, 1994). It helps to stabilize soil aggregates and therefore improves soil structure, drainage and aeration, important for avocado roots.

SOM is measured as soil organic carbon (SOC) for specified soil layer depths. It is obviously highest in the top 5cm, decreasing with depth. Some studies measure SOM only in the top 10cm; others every 10cm to a specified depth. Ideally, we need to know how much is in the rooting profile of the particular crop. “Topsoil” SOM, i.e. SOM in the A horizon, is a criterion for classifying soils in South Africa. “Humic” A horizons contain, *inter alia*, > 1.8% organic C (i.e. > 3.0% organic matter), and are found in highly leached (low base status), freely draining

topsoils in cool to cold, most climates. Their B horizons are usually well-drained, and often have high O.M. content (Soil Classification Working Group, 1991).

The orchard soil is one of the most important basic resources in avocado tree management. Avocados, in fact, have amongst the most exacting soil requirements, for good performance with minimal technological input and cost, of all fruit crops. A world view of avocado soil requirements, including the characteristics of an “ideal” soil profile was given by Wolstenholme (2002, 2013). Criteria for choice of avocado soils in South Africa were updated by Wolstenholme & Sheard (2011a; b). However, it is undoubtedly true that most orchards are not planted on ideal soils, and furthermore soil variability within orchards in rolling topography can be significant. Soil variability on a regional scale can be huge. Avocado soils on the Nelspruit Batholith, for example, vary from heavy red clays (up to 60% topsoil clay in higher rainfall areas), right through to coarse, gravelly sands with less than 10% clay (e.g. near Nelspruit).

Allied to soil clay content, and indeed quite strongly correlated with it, is soil organic matter (SOM) content. Both clay and SOM have colloidal properties, making them the store-house of positively charged mineral elements (cations) needed for plant growth, e.g. NH_4^+ , K^+ , Mg^{++} , Ca^{++} , and trace elements. They are also the main reservoirs of soil water. SOM is especially valued in soils, since it improves soil physical and biological properties, in addition to chemical properties, and it makes “organic farming” possible. It is also a key component of the integrated “Pegg Wheel” management package for *Phytophthora* root rot (Wolstenholme & Sheard, 2010), and promotes, as the food source, microbial activity and soil health.

All cultivated soils steadily lose organic matter for several decades before stabilizing at a much lower level. This loss of SOM is one of the most important factors associated with farming-induced soil degradation and the “sustainability” of farming - a worldwide problem. SOM content and quality are today central to assessing the quality of agricultural soils (Dominy & Haynes 2003; Dominy *et al.*, 2002). High SOM is truly a blessing to environmentally-conscious farmers. However, it must be properly managed.

It is important that every grower knows both the clay % and the SOM% of his soil – these are key management tools. A soil with 50% topsoil clay and 4 – 6% topsoil SOM, for example, is both very easy to over-irrigate (and subject to some saturation during high rainfall episodes), and will be high in plant available N due to SOM “mineralization”. A soil with 5 – 10% clay and < 1% topsoil SOM is a totally different proposition, being droughty and infertile, and best managed by the “little and often” approach to irrigation and fertilization (fertigation), due to its very poor ability to store water and fertility. Organic matter addition, mulching and composting are especially important in such stressful soils.

SOM figures must be treated with caution, as they are dependent on depth of sampling. If only the top 10cm is sampled, unrealistically high figures may result. As a general guide,

most S.A. *topsoils* (to 30cm depth) contain +/- 1% SOM. Topsoils under long-established pasture, or virgin grassland, may contain 5 – 8%. The shallow feeding root zone of tropical rainforests may have up to 25% SOM; peats 30 – 90%. A few S.A. avocado soils in the cool, moist climates on old relict plateaus in the sub-coastal belt of KwaZulu-Natal have “humic” A horizons with > 3.0% SOM, e.g. near Paddock, Umbumbulu, Wartburg/Bruyns Hill, Kranskop, Ndwedwe and Eshowe. Some diabase/dolerite derived topsoils in cooler, high rainfall areas near Kiepersol, and below Sabie and Graskop, and in the Tzaneen district, also have humic A horizons. Most S.A. avocado soils however, are *oxisols*, and are in Fey’s *oxidic* group (Fey, 2010).

By definition, *humic* A horizons have > 1.8% organic C (> 3% SOM); are moderately to strongly weathered with low base (K, Mg, Ca, Na) status, and overlie well-drained B horizons. In the S.A. soil classification scheme, they have names (soil form) like Inanda, Kranskop, Magwa, Lusiki and Sweetwater, depending on the properties of the subsoil. Within each form are subtypes, depending on aspects such as clay content, whether or not clay increases with depth, colour etc. - previously called soil “series” but now soil “families”. For example, Inanda soils with a thick (> 45cm) A horizon and a luvisc B1 horizon (i.e. marked increase in clay content) are referred to as Glenariff, or Mayfield for non-luvisc soils. Inanda type soils are physically amongst the best for avocados in South Africa, especially if their subsoil clay content does not exceed 35 to 40% (e.g. derived from Clarens sandstone). Higher clay (and SOM) contents, as when derived from dolerite or diabase, are harder to manage – requiring ridging to improve surface and internal drainage, and careful monitoring of soil and leaf N status.

None of our South African avocado soils have the SOM content of the volcanic, deep *andosols* of the Mexican highlands, with 4 – 6% topsoil OM combined with a sandy texture - the best avocado soils in the world. Our most common avocado soil form is ‘Hutton’, with “orthic” A on “red apedal” B, and typically 25 – 35% clay and 1 – 1.5% topsoil OM. Some of our Hutton soils in cool areas have SOM approaching the lower limit for humic A horizons, and could be called “humic Huttons”. An interesting new avocado venture on the slopes of Mount Rungwe in western Tanzania is on so-called mollic andosols derived from volcanic ash – very porous and very high in SOM.

How Much Plant Available N is Mineralized from SOM?

Firstly, to answer this question, how much SOM is there in the effective soil rooting zone - say to 1m depth for avocados? In sandy soils there may be only a few tonnes, but most typical sub-tropical soils would have > 50t per ha. Soils with humic topsoils and a high clay percentage (to protect the SOM) have > 200t per ha of organic topsoil C (340t/ha SOM), e.g. Mexican andosols, Australian krasnozems and South African humic soils. Fey (2010) cites the example of humic soils on the Koue Bokkeveld and Witzenberg plateaus in the W. Cape, planted to deciduous fruit trees, limed and fertilized with P and K. Potential N mineralization to 0.3m depth with 2% SOC, a soil C:N ratio of 10, and 5% annual SOC

mineralization, could be up to 400 kg N ha⁻¹ annually. This is about five times the annual N application to young pome fruit trees!

All SOM is subject to slow decomposition from soil micro-organisms - called "mineralization" because it recycles minerals back to the soil. N is released first as ammonium-N (NH₄⁺), which can be changed to nitrate-N (NO₃⁻). Both are available to plant roots, but only NH₄⁺ can be adsorbed onto clay and humus colloids. NO₃⁻ is easily leached beyond the root zone in very wet soils. This mineralized N is effectively "free" N to the grower. The greater the SOM content, the more of this "free", slow-release N is released for plant growth. Research by Meyer at the SASA Experiment Station at Mt. Edgecombe estimated that N mineralization potential varied from 75kg N per ha in low OM (<2%) soils, to about 150kg N per ha in high OM (> 4%) soils in the sugar belt - these are substantial amounts. High N mineralization rates were also suspected (Wolsitenholme & Whiley, 2002) in diabase-derived heavy clay soils in avocado orchards on old banana lands in the Kiepersol area.

It is important to note that only a small fraction of a soil's total OM is mineralized in one year, especially when SOM has stabilized after many years of cultivation. Most SOM is very stable and deeply buried, and therefore protected. Clay particles and high soil aluminium content similarly protect OM from mineralization. SOM decomposition, as previously noted, is favoured by heat, wet soils, soil cultivation (aeration) and liming. Frequent tillage quickly reduces OM content, but this is not favoured in avocado soils as it encourages Phytophthora root rot, and can compact soils. The high organic matter content of humic soils is due to their high degree of weathering, a cool climate, well-drained topographic position, soil faunal activity, and a high rainfall favouring dense grassland or forest over a long period of time (Fey, 2008).

Humus in particular, and also large pieces of wood, decompose very slowly. Humus is micro-organism excreta, and probably largely forms from lignin - it is a waste-product of microbial decomposition. Only a few per cent. of the humus "pool" mineralizes each year. Wood pieces are too large for much of the material to come into intimate contact with decomposer organisms - unless cut up they may persist for years, mineralizing very slowly. This is nevertheless a valuable source of "long-term", slow-release SOM and should never be removed from orchards after pruning. Even on high OM soils, its high C:N ratio will help (very slowly) to "mop up" excess N. On sandy soils it will contribute precious, scarce SOM. Similarly, pruned leaves and small shoots contribute to maintenance of SOM. Dead, naturally abscising avocado leaves have a higher C:N ratio than green leaves, as the tree salvages most mobile mineral elements (including N) before abscission. The natural dead leaf litter found under healthy avocado trees ("natural mulch") persists because it is mostly not in intimate contact with the mineralizing micro-organisms in the soil. It would disappear quickly if incorporated into the soil, but it is considered unwise to cut avocado feeder roots and thereby encourage PRR.

Recent S.A. Research on Soil Organic Matter

Prof. Dick Haynes, previously Prof. of Soil Science at the then University of Natal, Pietermaritzburg had a particular interest in soil biology. He noted that loss of SOM is still not regarded an important issue in S.A., in contrast to many other countries (Haynes & Hamilton, 1999). With his co-workers, he conducted very important research on this topic in K-Z-Natal. His review of soil biology and biochemistry research in S.A. (Haynes & Graham, 2004) is of great value.

One of the topics researched was deterioration of soil quality under sugar cane, aggravated by trash burning at harvest, rather than returning all crop residues to the soil. "Green" cane harvesting, leaving trash on the soil, significantly increased total SOM in the top 10cm, and increased the concentrations of various labile SOM fractions to 30cm depth. Benefits to soil structure, microbial and faunal activity, soil N supply to the crop and therefore sustainability of sugarcane mono-culture were anticipated (Graham *et al.*, 2002).

Other sugarcane research was on SOM in two different soils, a sandy coastal Glenrosa (18% clay) and a clay Hutton (62% clay) from the midlands, with long monoculture histories. Original organic C (in the top 10cm) at both sites was 40 – 50g C per kg. This declined exponentially with increasing years under sugarcane (trash burnt). For Glenrosa soil, it took 30 – 40 years to reach a new equilibrium at <20g C per kg soil. For the Hutton soil, after 20 – 30 years under cane the content was 33mg C per kg soil and not yet at equilibrium - slower decline due to protection of SOM by high clay content. It was concluded that traditional sugarcane production causes large declines in SOM, and deterioration of soil quality. Green cane harvesting, zero tillage and use of green manures were recommended (Dominy *et al.*, 2002)).

Haynes *et al.* (2003) researched effects of land use in the K-Z-Natal midlands on SOM and earthworms. In comparison to high SOM in native grassland, permanent kikuyu pasture increased SOM. Maize and sugarcane farming decreased SOM. Eucalypt and pine forests had similar SOM in the top 10cm to native grassland, but microbial biomass was higher. Earthworms (mainly exotic species) were most prominent in kikuyu pasture, and low in maize and sugarcane. Low earthworm numbers in exotic forests were due to low palatability of pine and gum litter (resins and tannins).

Earthworm numbers in the top 10cm in the Eshowe area, under a wide range of land use were highest under kikuyu pasture, followed in order by native forest, banana plantation, citrus orchards, *avocado* orchard (which was no different to wattle, pine, gum, grassveld and trashed sugarcane), with burnt sugarcane lowest. Actual SOM contents (top 10cm) varied from over 5.5% in kikuyu and native forest, over 4% under bananas, ca 3.5% for avocado, and ca. 3% for wattle (Dlamini *et al.*, 2001).

Mills & Fey (2004) found stocks of soil organic C (to 0.5m depth) in five untransformed indigenous South African sites varied from 21t ha⁻¹ in the Karoo to 168 t/ha in dense E. Cape succulent thickets. SOC stocks were also high in moist highland grassveld, especially if soil parent material was the more basic and fertile dolerite, as opposed to sandstone. Similarly, kikuyu and ryegrass pastures and pine plantations on dolerite soils had SOC stocks above 150t ha⁻¹. Soil N stocks in these soils varied between maxima of about 12 to 15. Soil C:N ratio in high SOM soils varied from about 12 to 16 in the top 10cm, decreasing with depth - reflecting high SOC in the surface layer (0 – 10cm). More fertile soils had higher SOM and clay content, and supported more vegetative growth and therefore more plant residues to build up SOM levels. Similarly, inorganic N fertilization, of kikuyu grass for example, produces more plant biomass and OM addition to the soil, and stabilizes the soil C : N ratio. To quote: “Nitrogen is required for the capture of carbon”.

The above research highlights the importance of SOM content in soil quality and farming sustainability. Although orcharding is more sustainable than annual row cropping, SOM is always there to be nurtured and appreciated. High SOM and annual OM inputs ensure “living soils” with good structure and greater potential for good yield. It is only in a few situations where growers have cause to view high SOM as a danger – specifically where its mineralization leads to excessive N release, unwanted vigour, and poorer fruit quality. However, this problem is faced by growers in Mexico, parts of Australia and New Zealand, as well as those with high clay/high SOM in K-Z-Natal and the northern provinces. Understanding the causes should lead to management strategies to minimize and “live with” the problem - in particular, reduction of inorganic N fertilizer inputs.

At the other extreme, the very low SOM (and clay) contents of some sandy, infertile and droughty soils in the low country near Nelspruit is a cause for concern, and everything should be done to improve the situation. Lower tree vigour does have advantages for fruit quality in the problematical Pinkerton cultivar, but the cost of avocado (and other) orcharding on such low potential soils is increased technology inputs (at greater cost), and eternal vigilance. Soil loss to erosion is also likely to be unsustainable.

In conclusion, SOM has a vital role to play in soil health, in the long-term sustainability of farming and orcharding, and as a means of storing C in the soil to help mitigate climate change on a global basis. Maintenance of SOC stocks, and their improvement where possible, is both imperative as well as the duty of those who are temporary custodians of the soil. It also makes good economic sense to do so.

Selected References for Further Reading

Borlaug, N.E. (2000). Ending world hunger. The promise of biotechnology and the threat of antiscience zealotry. *Pl. Physiol.* 124, 487-490.

Collier, P. (2008). The politics of hunger. How illusion and greed fan the food crisis. *Foreign Affairs* 87, 67-79.

Dlamini, T.C., Haynes, R.J. & van Antwerpen, R. (2001). Accidentally introduced exotic earthworm species dominate in soils on sugarcane estates in the Eshowe area. *Proc. S. Afr. Sugar Technol. Assoc.* 75, 217-221

Dominy, C. S. & Haynes, R.J. (2002). Influence of agricultural land management on organic matter content, microbial activity and aggregate stability in the profiles of two oxisols. *Biol. Fert. Soils* 36, 298-305.

Dominy, C.S., Haynes, R.J. & van Antwerpen, R. (2002). Loss of soil organic matter and related properties under long-term sugarcane production on two contrasting soils. *Biol. Fert. Soils* 36, 350-356.

Edmeades, D.G. (2012). Pseudo-science: a threat to agriculture? *Proc. 26th Ann. Conf. Grassland Soc. New South Wales*, pp. 38-47.

Fey, M. (2008). Soils of South Africa. Cambridge University Press, Cape Town. ISBN 978-1-107-00050-6. Pp. 287.

Graham, M.H., Haynes, R.J. & Meyer, J.H. (2002). Soil organic matter content and quality: effects of fertilizer applications, burning and trash retention on a long-term sugarcane experiment in South Africa. *Soil Biol. Biochem.* 34, 93-102.

Handreck, K.A. & Black, N.D. (1994). Growing Media for Ornamental Plants and Turf. University of N.S.W. Press, Randwick, Australia. Pp. 448.

Haynes, R.G. & Graham, M.H. (2004). Soil biology and biochemistry – a new direction for South African soil science? *S. Afr. J. Plant Soil* 21, 330-344.

Haynes, R.J., Dominy, C.S. & Graham, M.H. (2003). Effect of agricultural land-use on organic matter status and the size and composition of earthworm communities in KwaZulu-Natal, South Africa. *Agric. Ecosystems Envir.* 95, 453-464.

Miller, G.T. (1998). Living in the Environment: Principles, Connections, and Solutions. 10th ed. Wadsworth Publ. Co., Belmont, CA. ISBN 0-534-51912-1. Pp.xxiii + 759 + A80.

Mills, A.J. & Fey, M.V. (2004). Soil carbon and nitrogen in five contrasting biomes of South Africa exposed to different land uses. *S. Afr. J. Plant Soil* 21, 94-103.

Schaffer, B., Wolstenholme, B.N. & Whiley, A.W. (eds). The Avocado: Botany, Production and Uses. 2nd ed. CABI Publishing, Wallingford, U.K. ISBN 978-1-84593-701-0. Pp. xi + 560.

Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R. & Kapos, V. (2014). Global soil carbon: Understanding and managing the largest terrestrial carbon pool. *Carbon Management* 5, 81-91.

Soil Classification Working Group (1991). Soil Classification – Taxonomic System for South Africa. Memoirs on the Agricultural Resources of South Africa No.15. Dept. of Agric. Dev., Pretoria.

Whiley, A.W., Schaffer, B. & Wolstenholme, B.N. (eds). The Avocado: Botany, Production and Uses. 1st ed. CABI Publishing, Wallingford, U.K. ISBN 0-85199-375-5. Pp. xi + 416.

Wolstenholme, B.N. (2002). Ecology: climate and the adaphic environment. In: Whiley, A.W., Schaffer, B. & Wolstenholme, B.N. (eds). The Avocado: Botany, Production and Uses. 1st ed. CABI Publishing, Wallingford, U.K. ISBN 0-85199-375-5. Pp.71-99.

Wolstenholme, B.N. & Sheard, A. (2010). Integrated management of Phytophthora root rot: the “Pegg Wheel” updated. *Avoinfo* vol. 175, 11-15.

Wolstenholme, B.N. & Sheard, A. (2011). Selection and management of soils for avocados in South Africa. Part 1. General requirements. *Avoinfo* vol. 177, 9-16.

Wolstenholme, B.N. & Sheard, A. (2011b). Selection and management of soils for avocados in South Africa. Part 2. Modification and management. *Avoinfo* vol.181, 15-19.

Wolstenholme, B.N. & Whiley, A.W. (2002). Importance of the carbon : nitrogen ratio of organic materials in managing nitrogen in avocado soils. Document compiled for Avocado Study Group talks, Nelspruit and Kiepersol, Oct. 2002. Pp.3.

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