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Nitrogen – the manipulator element: Managing inputs and outputs in different environments

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ABSTRACT

Nitrogen (N) is the most important element in avocado nutrition. It has been called the manipulator element as there is a comparatively narrow optimum leaf range, varying slightly with cultivar and environment, associated with adequate vegetative growth and good yield of good quality fruit. Furthermore, N management aims to balance vegetative and reproductive growth, which are antagonistic. The N cycle has been strongly influenced by man's intervention, resulting in adverse effects on atmospheric, soil and water components. In most soils, organic matter (SOM) contains ca. 95% of "fixed" or potentially available N, temporarily immobilized and protected in clays, so-called amorphous compounds of Al and Fe, and soil aggregates. A very small fraction of this organic N is "mineralized" to plant-available ("reactive") ammonium (NH_4^+), nitrate (NO_3^-), and available organic N each growing season, especially from the surface soil layer when it is high in SOM, warm, moist, heavily limed, and well aerated (as by tillage). Soils derived from diabase (e.g. in parts of the Kiepersol and Burgershall areas) or dolerite (KwaZulu-Natal) are more clayey, more fertile, and have higher SOM contents than granite-derived soils. They can therefore have undesirably high levels of available N, leading to excessively vigorous growth of pruned trees. Management of such soils differs greatly from the sandy, low clay / low SOM soils found near Nelspruit.

This mini-review looks at inputs and outputs of "reactive" N in different environments, emphasizing SOM and its mineralization, and at consequent management of soil N. Excessive soil N leading to high fruit flesh N is also strongly implicated in certain fruit post-harvest disorders, and is probably the main controlling factor in the so-called 'Pinkerton' fruit quality problem. Understanding N mineralization in particular is critical for guiding N fertilization rates and timing in different soil types; the magnitude of other inputs and outputs is usually smaller but should also be known. A research study of N cycling dynamics and the available N budget in the three main types of South African avocado soils would be extremely helpful to managing this key element for avocado yield and good fruit quality.

INTRODUCTION

The current status of scientific knowledge on avocado nutrition was reviewed by Lahav & Whiley (2002). Previous reviews include Embleton & Jones (1966), Lahav & Kadman (1980) and Crowley (1992). General fertilization guidelines for South Africa were summarized by the SAAGA Research and Technical Working Group on Fertilization of Avocados (Anon., 1990) and more recently by Abercrombie (2001). Several field experiments on various aspects of avocado nutrition in South Africa have been reported (Du Plessis & Koen, 1991; Koen & du Plessis, 1991; Du Plessis *et al*., 1998).

Short overviews on individual elements in avocado nutrition include the trace element zinc (Crowley *et al*., 1996) and boron (Whiley *et al*., 1996). The major element nitrogen (N) is, however, undoubtedly the key element in avocado nutrition. It has been called the "manipulator element" (Whiley *et al*., 1988). This is because of its key role in the vegetative:reproductive balance, through effects on the tree vigour and bearing potential. Furthermore, unlike non-manipulator elements, for a given set of circumstances (soil, climate, cultivar, rootstock, management) the optimum range is very narrow. The older California literature, for example, specified that 'Fuerte' yields were highest with leaf N in the 1.6% – 2.0% range (Embleton & Jones, 1964). In contrast, high yields can be obtained with leaf Ca between 1.0% and 3.0%, Mg between 0.25% and 0.80%, or K between 0.9% and 2.0% – much wider ranges than N. This, therefore, allows for "luxury consumption" for non-manipulator elements, when increasing levels do not raise yield.

This is wasteful, both economically and environmentally.

What is often not fully appreciated by growers and advisers is that N management strategies must be tailored to specific environmental and management conditions, to achieve the same desired effect of a balance between vegetative vigour and yield (and fruit quality). This is because N inputs and outputs vary widely, especially between different soil types. The writer drew attention to the dangers of excessive soil N (Wolstenholme, 1989, 1990), particularly in soils high in soil organic matter (SOM), which usually are also high in clay content.

More recently, as the industry grappled with high density planting and pruning, it became abundantly clear that on some farms (and soils) tree vigour became extremely difficult to control, leading to poor yield and often also poor fruit quality (especially with 'Pinkerton' and 'Fuerte'). Investigations in the Kiepersol and Burgershall areas suggested that the main problem orchards were on heavy clay / high organic matter soils derived from diabase rather than granitic parent materials. The problem was exacerbated where there was a previous history of banana growing. Various documents were prepared, with inputs from SAAGA and ITSC personnel, explaining relevant aspects and suggesting remedies, i.e. the need for site-specific research (Wolstenholme, 2002; Wolstenholme & Whiley, 2002).

In contrast, orchards on the very sandy soils common to the Crocodile river valley near Nelspruit, derived from a different type of granitic rock under much less intense weathering and a more stressful climate, have a totally different N status. If we say that the diabase-derived heavy clays on some Burgershall and Kiepersol properties have, for most of the time, a positive N-balance, then the Nelspruit sands have a strong negative N-balance, i.e. their N requirements are much higher than the natural supply. It is of course not only the total seasonal supply that is important, but also the timing in relation to phenological growth stages of the tree (Whiley *et al*., 1988). In other words, N shortages or excesses can be more harmful at certain critical growth stages.

The majority of avocado soils in South Africa (Mpumalanga and Limpopo) fit somewhere in the middle, especially moderately clayey (20% –

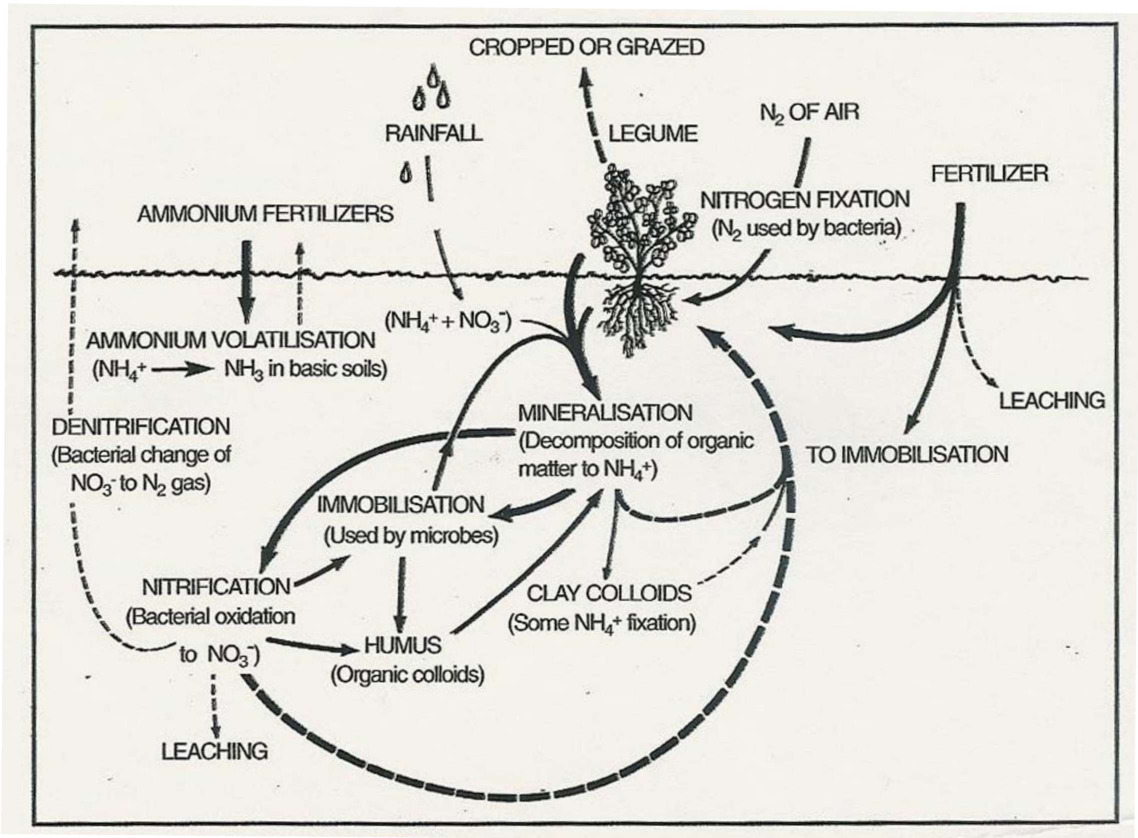

Figure 1. The nitrogen cycle, showing the inputs, transformation and losses (dashed lines) of nitrogen within the soil-plant-atmosphere system (from Miller and Donahue, 1990). The amount of change is indicated by the width of the lines. It should also be noted that the links to the fluxes to and from the oceans and rivers are not included in this diagram (from Otter & Scholes, 2003)

30% topsoil clay) soils derived from granitic parent materials. Most soils used for avocados in the KwaZulu-Natal midlands, however, are very clayey, being derived from dolerite (a much younger version of diabase) or shale. In the Wartburg / Bruyns Hill / Eshowe areas, Natal Group sandstones give rise to lighter textured soils, often with humic A horizons. N status is very dependent on topsoil organic matter, and previous history of cultivation.

The main objective of this limited review is to discuss N inputs and outputs in the main soil types used locally for avocados. Regrettably, there has been no committed research on the N balance or N budget in avocado soils. However, some of the research in adjacent forestry and conservation areas is partly relevant (as is sugarcane nutrition research in KwaZulu-Natal), and sometimes allows guesstimates as to inputs and outputs. Whether soils are N positive, N neutral or N negative will affect the N fertilization programme, or lack of it. It will also be stressed that inputs of plant-available N ("reactive N") come from several sources apart from N fertilizers, while there are several mechanisms by which available (reactive) N can be lost. We lack detailed accounting of inputs and outputs, i.e. the N supply and loss pathways, but an understanding of basic principles is helpful for management.

Finally, the environmental pollution potential of reactive N forms is a cause for concern, so much so that N has been called "the essential public enemy" (Dalton & Brand-Hardy, 2003).

THE NITROGEN CYCLE

The earth's atmosphere is made up of 80% nitrogen gas (N_2, or $N \equiv N$). However, this is an inert, chemically non-reactive form. For nitrogen to become reactive, the triple bond needs to be broken, e.g. in the industrial, energy-demanding Haber-Bosch process to make ammonia (NH_3), or naturally by so-called N-fixing bacteria in legume root nodules. "Reactive N" includes ammonia (NH_3), the ammonium ion (NH_4^+) and nitrate (NO_3^-) forms are taken up in large amounts by roots – these are the dominant plant "available" forms of N. The NH_4^+ form can be converted to NO_3^- in the soil by nitrifying bacteria.

Nitrogen therefore exists in several reactive (fixed) forms, and transformations occur between

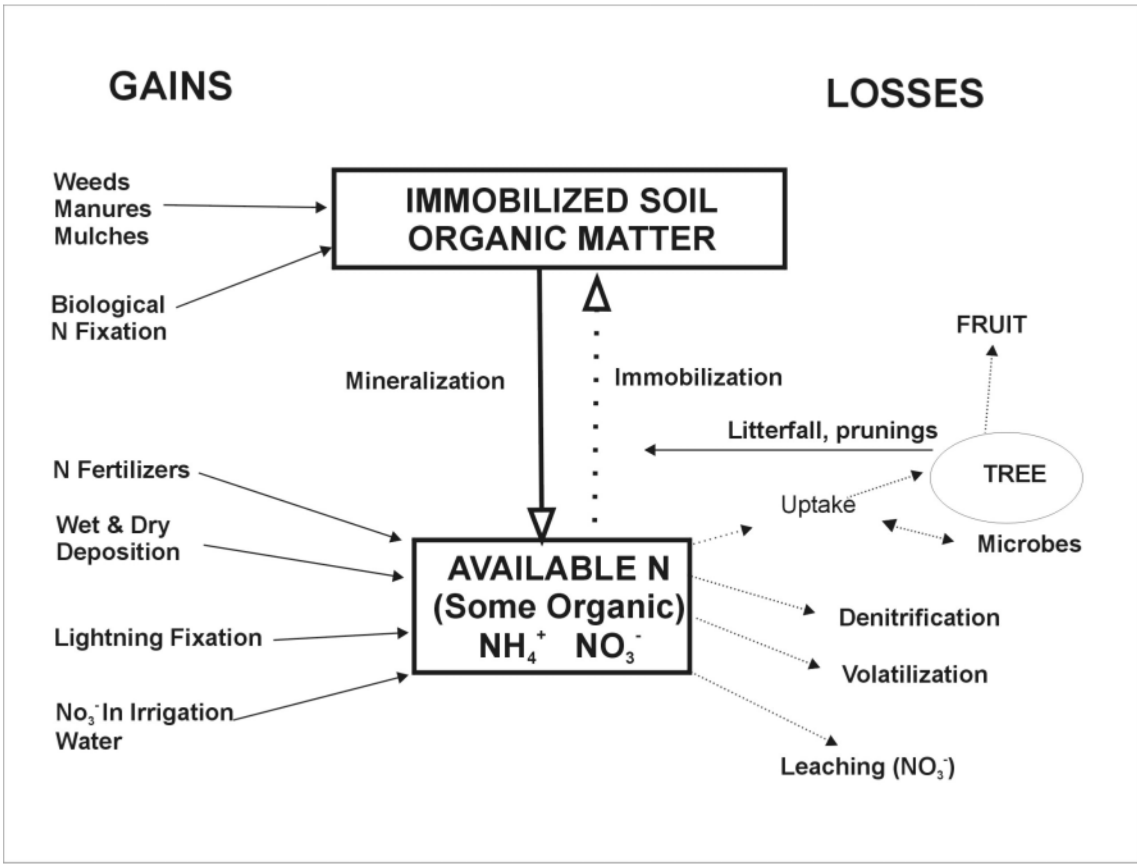

Figure 2. A simplified representation of gains (inputs) and losses (outputs) of plant available (mainly NO_3^- and NH_4^+) nitrogen in an orchard. The largest store of potentially available N (after depolymerization and mineralization) is SOM; the tree itself also becomes a major store. Major losses are from leaching and fruit export. N is internally recycled in the tree

reactive forms and the N_2 gas of the atmosphere. The N cycle shows these transformations diagrammatically within the soil-plant-atmosphere system (Figure1). Since the industrial revolution and the invention of the Haber-Bosch process, our activities have markedly changed the global N cycle, especially by N fertilization, livestock farming, soil tillage, burning, and overloading the system with industrial reactive N pollutants. The creation of reactive N has changed from being dominated by natural processes, to human activities (Galloway *et al*., 2002). Nitrate pollution of groundwater by agricultural activities is of great concern. EurepGap certification now requires, *inter alia*, adherence to rigid standards for nitrate content of water, which can become unacceptably high in areas of intensive animal enterprises, cropping and high N fertilization rates – especially in farm dams during drought years.

From an orchard point of view, it is helpful to think of INPUTS (gains) and OUTPUTS (losses) of reactive N to the soil during a given season. The balance between the two determines the quantity of "available N" for plant growth. We can then talk of orchard N budgets, which will ultimately be reflected in tree vigour and leaf N levels. Unfortunately, from an orchard management point of view, we are dealing with a very dynamic and ever-changing *soil* environment, so that it is rare to analyse soil specifically for "available N" content. Nevertheless, some idea of the amounts involved (gains vs losses) on a broad scale, is imperative to understanding the situation on a particular farm, and to intelligent decision making.

REACTIVE NITROGEN INPUTS AND OUTPUTS

Inputs of reactive N to the soil, as well as outputs, are shown diagrammatically in Figure 2. From a farming point of view, NH_4^+ (ammonium) and NO_3^- (nitrate) forms, which can be taken up by plant roots, are ultimately of most importance. However, these usually occur in comparatively low concentrations at any one time, compared to "potential" (immobilized) available N. The latter is stored in organic forms in soil organic matter, soil fauna and micro-organisms (and in the plant), and in other forms of reactive N which can be converted to plant available N.

Before inorganic N fertilizers became available, biological N fixation, mainly by legumes, was the main source of "available" N in the N cycle. Most natural ecosystems were N limited, and N was the major limiting factor. Farmers included legumes in crop rotations, and were very conscious of the importance of maintaining and building up soil organic matter (SOM), in which organic N can be stored. This represents N "capital", from which "interest" can be earned by SOM mineralization, releasing, in a controlled fashion, the necessary available NH_4^+ and NO_3^- (and some "available" organic N) for the plant's N

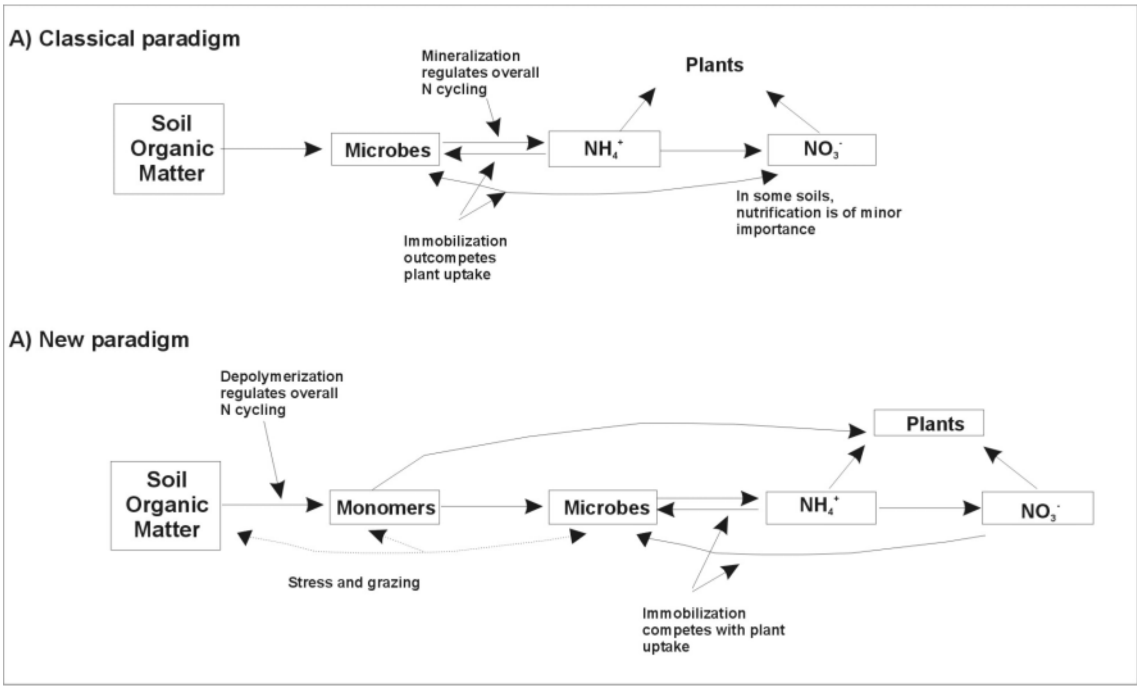

Figure 3. The changing paradigm of the soil N cycle. (A) The dominant paradigm of N cycling up through the middle of the 1990's. (B) the paradigm as it developed in the late 1990's. From Schimel & Bennet (2004)

Table 1. N and S mineralization potential of some soil forms, based on their organic matter context (SOM) (adapted from Anon., 1999)

N & S mineralization Potential	Soil forms	SOM (%)
Low	Glenrosa (light)	<2
Moderate	Glenrosa (heavy), Hutton (light)	2-3
High	Hutton (heavy, mod.), Shortlands	3-4
Very high	Inanda, Kranskop, Magwa, Lusikisiki	>4

needs. Inorganic N fertilizers changed things dramatically, providing concentrated and cheap forms of available N. By 1970, according to Galloway & Cowling (2002), the amount of available N released from N fertilizers approached the amount fixed naturally (biologically) on land (ca 90 Tg N an^{-1}).

By the year 2000, total reactive N inputs from human activities were ca 165 Tg N an^{-1} (100 Tg from inorganic N fertilizers, 20 Tg from burning fossil fuels, 20 Tg from human food ingestion, and 20 Tg from other uses of Haber-Bosch fixed N) (Galloway *et al*., 2002). Other aspects of human influence on the N cycle are summarized by Otter & Scholes (2003). It is clear that modern farming is a huge intervention into the N cycle, and that intensive orcharding has the potential to aggravate "leaks" of reactive N into surface and ground water. On many soils, in fact, over-fertilization (excessive inorganic N inputs) occurs, and is a problem not only to the environment, but also to avocado tree performance (Wolstenholme, 1989, 1990, 2002).

REACTIVE N INPUTS TO ORCHARD SOILS

The main sources of reactive N in orchard soils are soil organic matter, which is slowly mineralized to available NH_4^+, which in turn can be nitrified to NO_3^- (both forms are available for uptake by plant roots); breakdown of other organic sources of N such as manures, litter, and N-rich cover crops or mulches; biological N fixation by legumes and non-symbiotic N fixing plants; atmospheric deposition of reactive N (both wet and dry); N from inorganic fertilizers; and small amounts of N fixed by lightning.

Worldwide, it is estimated that the soil organic fraction accounts for ca 95% of the total soil N pool (Söderlund & Svensson, 1976), although Baldock & Nelson (2000) cite examples of 90% – 97%, with the *inorganic* plant-available pool constituting only 1% – 3%. An average C/N/P/S ratio of 107: 7.7:1:1 was given by Stevenson (1986) for SOM. The C : N ratio of SOM depends on the vegetation inputs and the degree of decomposition, but is usually 12 – 16 when fully decomposed (Baldock & Nelson, 2000). These authors state that perhaps the most fundamental function of the organic fraction is the provision of energy for microbes to drive soil biological processes, including mineralization. Most SOM is found close to the soil surface, and measurements of SOM must therefore specify soil depth, e.g. the 0-20 cm or 0-40 cm layer.

Of the soils of interest to avocado growers in South Africa, SOM contents are highest in humic A horizons. Topsoils with >1.8% organic carbon (i.e. >3.5% SOM), occurring in very leached, acid, well-drained soils, are classified as *humic* A horizons in the South African soil classification system (Soil Classification Working Group, 1991). Such high SOM contents in well-drained soils only develop in relatively cool, moist, inland mistbelt areas on ancient relic plateaus in South Africa, e.g. at Paddock, Umbumbulu, Wartburg / Bruyns Hill, Kranskop, Eshowe, Ngome, Ndwedwe and Melmoth in KwaZulu-Natal. They usually develop in dolerite-derived soils, but also on Pietermaritzburg shales, and on Natal Group Sandstone (sandier subsoils). The status of humic topsoils in avocado-growing soils in Mpumalanga and Limpopo is uncertain, but such soils probably exist on diabase-derived soils in higher-lying areas in the Kiepersol area, and especially in forestry areas closer to the escarpment. As SOM (the organic remains of plant material, soil organisms and animals, ultimately forming relatively stable humus) is rich in immobilized organic N, soils high in SOM have a relatively stable, long-term, slow-release reservoir of plant available N when mineralized by soil micro-organisms (using the SOM as an energy source) (Anon. 1999). Mineralization also produces plant available sulphur (S) and phosphorus (P).

Soils with humic A horizons have been rated as amongst the best in South Africa for avocados, from a physical point of view (Wolstenholme & le Roux, 1974). However, they are eclipsed by the andosols of Mexico and New Zealand (Wolstenholme, 2002). Chemically they can be problematical due to the high available N content and low available P content, and therefore require amelioration and fertilization (Wolstenholme & Whiley, 2002).

Most South African avocado soils have much lower contents of SOM in the topsoil, or in the top 20 cm to 40 cm. This applies particularly to the granite / granitic and sandstone-derived soils, in which 1% – 2% SOM is typical. SOM in such soils is correlated with clay content. Higher rainfall soils, with higher clay contents and supporting more luxurient vegetation, have higher SOM content than the much sandier soils, e.g. the Crocodile river valley near Nelspruit.

Mineralization of Soil Organic Matter (SOM): The process

Mineralization of immobilized SOM to plant available forms of *inorganic N* was regarded as the key step in the N cycle until the 1990's. New research now shows that some simple *organic* forms of N, e.g. amino acids, amino sugars, peptides and proteins are present in the soil N pool, and are used as N sources by plants and microbes. These organic N "monomers" may even dominate N uptake in ecosystems which have very low N availability, e.g. deserts, and Alpine and wetland systems. In situations where N availability and uptake is intermediate, organic N uptake declines and NH_4^+ forms (from mineralization) dominate. Finally, at very high N availability, as in many agricultural systems and N-rich tropical forests, NO_3^- is the dominant form of available N, as conditions favour nitrifying organisms (Schimel & Bennett, 2004).

Schimel & Bennett (2004) discuss the broadened definition of N mineralization, in which N cycling is driven by depolymerization of N-containing polymers (in SOM), by microbial (including mycorrhizal) extracellular enzymes. The resulting smaller, *organic* N-containing monomers (e.g. amino acids) can be directly used by plants or soil microbes (the latter constituting mineralization). This depolymerization step is now regarded as the critical rate-limiting step in N cycling. Recent research also pinpoints soil microsite differences in N cycling – there are microsites where net N mineralization dominates, and others where net N immobilization (return to bio-unavailable polymeric forms) dominates. Mycorrhizal fungi help plant roots not only by increasing their absorptive surface area, but may also supply enzymes for depolymerization, helping plants to compete against microbes for available N. The classical view of N cycling, and the new paradigm (Schimel & Bennett, 2004) are shown in Figure 2. From a horticultural point of view, this may be regarded as academic.

Mineralization of SOM: How much?

The question arises as to how much available N is mineralized annually in soils with varying SOM contents. Meyer *et al*. (undated) provided early estimates for Natal sugarbelt soils incubated in the laboratory. They concluded that N mineralization potential varied from 150 kg $N.ha^{-1}an^{-1}$ in soils with high SOM (>4%); 75 kg – 150 kg $N.ha^{-1}an^{-1}$ in soils with medium SOM (2% – 4%) and <75 kg $N.ha^{-1}an^{-1}$ in low SOM soils (<2%). Such potential values are unlikely to be reached under orchard conditions, but even if halved, these are still substantial amounts. Agrella *et al*. (2003) estimated that an Inanda form clay soil at Lusikisiki supplied ca 80 kg $N.ha^{-1}an^{-1}$ through mineralization.

We should note that only a small fraction of total SOM is mineralized in any one season. Australian krasnozems (equivalent to humic oxisols developed from diabase or dolerite in South Africa) with high clay and SOM content, have >200 t organic C ha^{-1} (>340 t ha^{-1} SOM) (Oades, 1995) to 1 m depth. This is the stored (immobilized) organic N (“capital”), and the mineralized inorganic N represents the available N (“interest”) after microbial decomposition. Most of our avocado soils, derived from granitic rocks, would have much lower mineralization potential.

Soil forms of the sugar industry are classified into four groups for N (and S) mineralizing capacity, based on their SOM content (Anon., 1999). The following examples are selected soil forms used for avocados in South Africa.

Mineralization of SOM is affected by environmental factors (temperature, moisture, aeration, pH, P level) and by types and amounts and C/N ratio of organic N and C present (Louw & Scholes, 2002). High soil temperature combined with high moisture availability and good soil aeration (e.g. recent tillage) favour rapid mineralization in cultivated soils. Soils which are brought under cultivation initially lose SOM rapidly, until an equilibrium is reached.

Dominy & Haynes (2002) and Dominy *et al*. (2002) have documented SOM losses under various cropping regimes, and for contrasting soils, in KwaZulu-Natal. Undisturbed vegetation sites had 4% – 5% organic C (multiply by a factor of 1.72-2 to get % SOM, depending on the C content of SOM, usually in the range of 50% – 58% according to Baldock & Nelson, 2000) in the top 0-10 cm layer. Under sugarcane, SOM in a sandy Glenrosa soil reached a new equilibrium of 1.7% organic C after 30-40 years monoculture. In contrast, in a clayey Hutton soil (ca 62%), the organic C declined to 3.3% after 20-30 years sugarcane monoculture. Similarly, different land uses affected the rate of decline of organic C in a trial on two KwaZulu-Natal oxisols, with maize and sugarcane causing fast declines in comparison with kikuyu pasture, and annual ryegrass pasture.

Similarly, Graham *et al*. (2002) quantified the adverse effects of burning sugarcane in KwaZulu-Natal as opposed to retention of trash, on SOM and microbial biomass. Green cane harvesting increased yields, and in particular the labile fraction of SOM. Haynes *et al*. (2003) noted large differences in both SOM and in composition of the earthworm communities with different land use in KwaZulu-Natal. Permanent, grazed dairy pastures had the highest SOM and microbial biomass C, and the largest and most diverse earthworm communities. Pine and eucalypt plantations had high SOM and microbial biomass C, but low earthworm communities – presumably due to low palatability of pine and eucalypt litter (resins and tannins; very acidic topsoil).

Mineralization of SOM also depends on its composition, especially the proportion of more labile as compared to “protected” fractions. Biological stabilization of organic C against decomposition occurs through soil mineral components, such that the rate of decomposition of older, protected C is balanced by younger organic C – the equilibrium state in undisturbed soils. Some organic C is protected for long periods, even centuries, e.g. through entrapment between layers of clay plates (Theng *et al*., 1986). Soil structure can limit the accessibility of organic C to decomposer micro-organisms, and of micro-organisms to faunal predators, through stable aggregates, e.g. clays encapsulating organic materials (Tisdall & Oades, 1982); burial of organic C in aggregates (Golchin *et al*., 1994), and entrapment in small pores (Elliott & Coleman, 1988). The formation of Al organic complexes is also important to biological protection of organic C in andosols. Amorphous Fe compounds and Fe^{3+} cations have a similar protective effect on organic C (Boudot *et al*., 1986).

It is therefore not surprising that liming of acid soils high in clay and SOM, also increases mineralization of SOM, and the release of substantial amounts of inorganic, available N. Fertilizer trials on such soils at Ntabamhlope in KwaZulu-Natal in the 1950's showed that there was no response of maize to fertilizer N for 20 years, as long as soils were limed, and available soil P was raised by superphosphate (Sumner, 2003, personal communication). Liming reduced Al toxicity, and presumably speeded up N mineralization from protected organic C.

It is clear that SOM content is a key factor in N fertilization of avocado. It varies widely with soil parent material and climate – so much so that site-specific N fertilization programmes are needed. In the Kiepersol / Burgershall area of Mpumalanga, for example, adjacent farms may need very different N fertilizer programmes. Diabase-derived old banana soils, high in SOM and clay, may need only minimal N addition – especially in pruned (invigorated) and heavily limed orchards (faster mineralization of SOM). Granitic soils with lower SOM and clay content will need intermediate N fertilization rates. Very sandy granitic soils in the Nelspruit area will require the heaviest N application, preferably in frequent small doses as in fertigation.

The site-specific fertilization need has been recognized in some forestry site classification schemes in South Africa (Louw & Scholes, 2002). Herbert (1992) evaluated fertilizer trials with *Eucalyptus grandis* and noted the relative responses to applied N and P as a function of SOM. For N, tree growth responses were inversely related to mineralizable topsoil organic matter – until at 4% topsoil organic C (ca 6.8% SOM) there was no increase in growth. In contrast, the higher the SOM the greater the response to P fertilization.

Organic fertilizers, ameliorants, mulches and litter

Any organic material applied to orchard soil will contain immobilized, organic N. Depending on its C : N ratio as well as structural characteristics, this organic material is subject to microbial decomposition or mineralization, thereby adding inorganic N to the soil for use of plants, and microbes. This includes recycled plant litter. Organic materials can be regarded as slow release fertilizers if they are relatively high in N (and P, S, etc). Litter (dried leaves, twigs, flowers, etc.) and mulches will be comparatively low in N. For our purposes, the C : N ratio is useful. High C : N ratios, i.e. above 30 and especially above 100, are more typical of mulches which are applied to soils high in available N. They help to "mop up" surplus N. Materials with low C : N ratios (below 20 to 30), will increase total soil available N as they are decomposed, and are therefore more useful for sandy, infertile soils. Speed of decomposition is also important – large branches will decompose far more slowly, even over years, than smaller and more succulent material. Contact with soil micro-organisms is also required. This topic is explained in detail by Handreck & Black (1994), while Wolstenholme & Whiley (2002) dealt with its significance in the management of soil N in avocado orchards.

Symbiotic and non-symbiotic N fixation

In natural ecosystems, symbiotic N fixation by bacteria in root nodules of legumes is the main source of N. Some non-leguminous plants also fix some N. On root decay, or after incorporation into the soil, this organic N is mineralized by microbes into available inorganic N. Legumes are unlikely to be very prominent or welcome in avocado orchards, except perhaps as a cover crop (velvet or dolichos beans, sunnhemp) in non-bearing orchards in N deficient soils. There is no space for cover crops in modern high density orchards. This potential input of available N can almost be discounted in bearing avocado orchards.

N fertilizers, inorganic and organic

Most growers, based on annual leaf analysis and less frequent soil analysis, use inorganic N fertilizers such as limestone ammonium nitrate, urea, and on alkaline soils ammonium sulphate, to make up any deficiencies in N supply to the tree. Alternatively, mixtures of N and other elements, e.g. potassium nitrate, monoammonium phosphate, or N:P:K mixtures, both for solid or liquid (fertigation) applications, are used. Organic growers would use only organic N sources with low C : N ratio, e.g. manures, chicken litter, relying on "slow release" available N from microbial decomposition.

Fertilizer rates will naturally depend on the magnitude of other N inputs, especially SOM content, as well as natural soil fertility, climate, crop load, etc. There are situations where no N fertilization is necessary for several years, as the soils have a positive N balance. To cater for high N needs at critical periods, one or two LB urea sprays (1%) may suffice. At the other extreme, application rates up to 400 kg $N.ha^{-1}an^{-1}$ are used in Israel (Hofshi, 1996) – indicative of a substantial negative N balance, as well as a climate less conducive to vigorous growth, and management strategies inducing vigour through pruning, counteracted by use of growth retardants, e.g. Sunny®.

Wet and dry deposition of reactive N

It is not generally realized that reactive N pollutants (and those of sulphur) can be deposited from the atmosphere. Dry deposition occurs from small particles in the atmosphere; wet deposition in rain, mist and fog. Excellent reviews of N deposition in the northeastern U.S.A. (Aber *et al*., 2003) and the western U.S.A. (Fenn *et al*., 2003a, b) are available. For areas close to South African avocado growing localities, the Kruger National Park study of Scholes *et al*. (2003) is instructive. Significant research on N cycling has also been conducted in forestry soils of the Mpumalanga escarpment (Dames *et al*., 2002; Bird & Scholes, 2002; Louw & Scholes, 2002).

The main emission sources for reactive atmospheric N are transportation, coal-burning power plants, industry and agriculture. The western U.S.A. even receives transpacific atmospheric N from industrializing S.E. Asia. Most combustion processes for producing energy or for transport produce significant amounts of nitrogen oxides – not surprisingly as fossil fuel combustion occurs in an atmosphere of 80% gaseous N (Dalton & Brand-Hardy, 2003). This will also apply to biomass burning. Coal-fired power stations on the Mpumalanga highveld cause significant downwind N deposition in the eastern escarpment areas, and even in Kruger Park. According to Fenn *et al*. (2003a), nitrogenous emissions from transportation, industry and power plants are dominated by NO_x; those from N fertilization of crops, and concentrated animal feeding operations are mainly reduced forms (ammonia [NH_3] and ammonium (NH^+_4)], collatively referred to as NH_x. N deposition causes enrichment of systems that are naturally N limited (Fenn *et al*., 1998). This results in increased plant growth, but will favour some plants selectively, leading to changes in plant and animal communities. Other changes include increased nitrification rates and higher NO_3 levels in soils, rivers, dams; eutrophication of water (for which raised P concentrations are also required), and deterioration of drinking water quality. In urban areas and downwind of them, increased emissions of nitrogen oxides (NO_x) can lead to raised ozone (O_3) levels, which can cause injury to sensitive plant types.

What is the extent of atmospheric N deposition? In California, deposition exceeds 90 kg $N.ha^{-1}an^{-1}$ in bad fog years in the Los Angeles basin and surrounding mountains, although 20 – 45 kg is more normal (in spite of strict anti-pollution legislation). NH_x emissions are about 50% more than NO_x emissions (Fenn *et al*., 2003a). Deposition of >15 kg $N.ha^{-1}an^{-1}$ is regarded as high. In South Africa, most studies relate to the Savanna Ecosystems Project. Near Skukuza in the Kruger National Park, downwind of highveld coal-burning power stations, deposition was estimated at 21.6 kg $N.ha^{-1}an^{-1}$, of which dry deposition was 15 kg N (8 kg in NH_4^+ form). Wet deposition constituted 3.2 kg N as NO_3 and 3.4 kg $N.ha^{-1}an^{-1}$ as NH_4^+. Wet deposition could be expected to be more in higher rainfall areas along the escarpment, contributing to acid rain. In contrast, at Nylsvley (upwind of the power stations) and in Zimbabwe, deposition was estimated at 1.66 – 4.01 kg $N.ha^{-1}an^{-1}$ – these can be regarded as "background" levels (Scholes & Walker, 1993; Scholes *et al*., 2003). Interestingly, wet and dry deposition of sulphur (S) was estimated at 5.7 and 8.2 kg S $ha^{-1}an^{-1}$ respectively (Olbrich, 1995; Scholes & Scholes, 1999). The writer has not seen equivalent figures for the Crocodile river valley downwind of the Ngodwana pulp and paper complex, but it is in the interest of crop agriculture that they are publicized. Biomass burning also contributes to N deposition. Acidification of soils is already a serious threat in South Africa (Fey, 2001).

Lightning fixation of N

Lightning possesses sufficient energy to break the strong $N \equiv N$ bond of atmospheric nitrogen (N_2), so that the N atoms can combine with H or O and become reactive N. However, the amounts of N fixed in this manner are comparatively small. An average of ca 10 kg $N.ha^{-1}an^{-1}$ is probably typical for areas with moderate rainfall and occasional thunderstorms.

Available N in irrigation water

Reactive N in water is used as an index of ecosystem N overload, measured as nitrate (NO_3^-) concentration. Strict legislation applies in developed countries to prevent pollution of surface and groundwater. For purposes of human drinking water, NO_3^- levels must usually be below 40 mg L^{-1}or 50 mg L^{-1}. Nitrate pollution is more likely in arid or semi-arid areas, where low rainfall means less dilution of contaminants. Similarly, dams which are not regularly flushed by flowing water may be in danger of NO_3^- buildup. If this is combined with significant phosphorus inputs, as from heavily fertilized fields or animal feedlots, eutrophication of water occurs with accompanying algal and other aquatic plant growth.

Irrigation water will always apply some dissolved salts to irrigated soil, and this increases with lower rainfall. Most avocado areas in South Africa are in relatively high rainfall localities, so NO_3^- inputs are likely to be low. Growers should nevertheless be aware of the extent of the addition on an annual basis. An early fertilizer trial in Israel was later found to be compromised because the substantial NO_3^- content of the irrigation water was not recognized (Lahav, E., 2003, personal communication).

REACTIVE N LOSSES FROM ORCHARD SOILS

Reactive N is lost from the orchard in the harvested fruit, in direct proportion to crop yield. Leaching of soluble NO_3^- into groundwater also represents a loss of root-available N. Available forms of N can also be denitrified to NO, N_2O and gaseous N_2, which are lost to the atmosphere. Similarly, NH_4^+ can be volatilized to NH_3 (ammonia gas), and NH_3 losses from surface applied manures also occur – the loss to the atmosphere being called NH_3 volatilization. Very little of any of these gaseous losses are likely to be returned to the orchard (as wet deposition) and therefore constitute net losses of available N. In addition, any removal of vegetation from the orchard, e.g. tree prunings or weeds, constitutes a net loss of potentially available N (and organic matter). Lastly, although highly unlikely in orchards, any burning of biomass causes losses of potentially available N.

N losses in harvested fruit

Lahav & Kadman (1980) reported losses from the harvested fruit in a 10 t ha^{-1} crop (cultivar unspecified), which was the surprisingly low figure of 11.3 kg $N.ha^{-1}$. Figures for other macronutrients were 1.7 kg P, 19.5 kg K, 2.1 kg Ca, 5.0 kg Mg and 8.0 kg S. In a review of avocado nutrition, Lahav (1998) gave the same figures (as do Lahav & Whiley, 2002) but also stated that a 15 t ha^{-1} crop removes 40 kg N. Lahav (1998) noted that all the N removed in a 10 t crop (11.3 kg N) would be replaced by a fertilizer application of 55 kg ha^{-1} of ammonium sulphate (21% N). This of course assumes 100% N take-up by roots, whereas between one-third and two-thirds or more is usually lost by leaching and volatilization. Abercrombie (2001) states that 1 t of avocado fruit removes ca 1.96 kg $N.ha^{-1}$; on this basis 19.6 kg N is removed by a 10 t crop. Again, cultivar is not specified. Marchal & Bertin (1980) found that the proportion of N appropriated by the fruit in a seven year old 'Lula' avocado in Martinique was 5.5%. In contrast, Lovatt (1996), for large high-yielding trees (100 kg $tree^{-1}$), found that 26% of the tree's N was in the mature fruit, ca 50% in branches, 18% in leaves and 4% in roots. Stassen *et al*. (1997), for 6 year old 'Hass' trees, measured ca 16% of the tree's N in fruit at harvest (av. 35 kg $tree^{-1}$), 25% in leaves, 15% each in shoots and wood, 10% in bark and 19% in roots. N concentration at harvest was 1.23% in flesh and 0.45% in seed. They estimated, from this preliminary one-season study, that a total of 321.2 g N (of which 125.2 kg was in the fruit) had to be taken up by the tree to produce 35 kg of fruit, i.e. 9.2 g per kg of fruit, or 9.2 kg N per tonne of fruit. This appears to ignore recycling of N taken up previously, and not lost to the tree by fruit harvest and litter fall. The most recent nutrient removal figures are provided by Salazar-Garcia & Lazcano-Ferrat (2001). They analysed fruits of 'Hass' (23.2% dry matter, or 76.8% moisture) and 'Choquette' (16.1% D.M., or 83.9% moisture) in Mexico. Nutrient removal by the crop was much higher in the smaller 'Hass' fruits with their higher dry mass. A 20 t ha^{-1} 'Hass' crop removed 52 kg $N.ha^{-1}$ (figures for P were 21 kg ha^{-1}, and for K 94 kg ha^{-1}), i.e. "exported" from the orchard. This is equivalent to 26 kg ha^{-1} of N for a 10 t ha^{-1} crop.

It is apparent that fruit N "export" figures vary widely between these studies – a 10 t ha^{-1} crop removing 11.3, 19.6 and 26 kg N in the fruit, respectively (only the last two figures specifically name 'Hass' as the cultivar studied). Doubling these figures for a good 20 t ha^{-1} crop gives 22.6, 39.2 and 52 kg N in the harvested fruit. Further work is needed, and fruit D.M. (or moisture) content affects the issue, as do crop load and cultivar. It should also be noted that Wolstenholme (1991), in comparing fruit nutrient export of avocado, orange and apple, used Lahav & Kadman's (1980) figures for avocado, which may be too low for a modern, high density 'Hass' orchard.

What is not in dispute, however, is that avocado fruits remove comparatively low amounts of N (and other nutrients) from the orchard when harvested, certainly in comparison with high-yielding sugar-storing fruits such as citrus and apples (and pineapples and bananas, according to Marchal & Bertin, 1980). Lahav (1998) suggested that mature orchards may have sufficient N cycling within the system to support normal growth and production. Marchal & Bertin (1980) also show considerable N reserves in leaves and twigs, roots and trunks of seven-year old 'Lula' trees. Wolstenholme & Whiley (1999) suggested that the evolutionary ecology of avocado trees led to very efficient hoarding and recycling of nutrients within the tree. N is retained in trees for extended periods of time. These strategies would reduce the overall N fertilization needs of avocado as compared to other evergreen tree crops.

Leaching of nitrate N

Nitrate (NO_3^-) losses through leaching beyond the root zone, and over time into groundwater, as well as runoff losses, are losses of available N to the orchard ecosystem. Nitrate N is much more subject to leaching due to its water solubility, and the negative charge precludes adsorption to negatively charged topsoil clay and humic colloids. Ammonium (NH_4^+) ions are, in contrast, adsorbed to soil clay and SOM colloidal particles and therefore protected from leaching. Sandy soils are likely to lose more NO_3^- to leaching, as their CEC and water storage ability are much lower than clay soils. Irrigation and / or rainfall have a greater chance of leaching the NO_3^- before roots can intercept it. Stassen *et al*. (1997) for example, used a figure of 20% leaching of N on a soil with 20% clay.

It must however be remembered that some subsoil *anion* exchange capacity (AEC) is a feature of highly weathered oxisols, andosols, ferralsols and krasnozems, typical of avocado areas in the world's humid subtropical localities (i.e. a net *positive* charge in the subsoil) (Shoji *et al*., 1993; Moody, 1994; Buol & Eswaran, 2000). Chemically, highly acid soils dominated by kaolinite clay and oxides of iron (Fe) and aluminium (Al) have a very low topsoil cation exchange capacity (CEC), i.e. poor ability to store cations for exchange with plant roots. Furthermore, kaolinite, oxides of Fe and Al, and organic matter have "variable charge" characteristics depending on pH value etc., i.e. low CEC in the negatively charged topsoil, but fairly high anion exchange capacity in the subsoil (negative charge). This means that they can, in the subsoil, adsorb anions such as NO_3^-, sulphate (SO_4^-) and phosphate (PO_4^-) for root uptake. Nitrate N can therefore accumulate in many oxisol / krasnozem subsoils, negating leaching and NO_3^- contamination of groundwater to some extent (Moody, 1994; Buol & Eswaran, 2000).

Denitrification to N_2O, NO and N_2

Denitrification is the reduction of available soil NO_3^- to the gases N_2O, NO and N_2. It is the only point in the N cycle where fixed N re-enters the atmosphere as N_2, thereby closing the N cycle and keeping the atmospheric N_2 concentration constant. It is especially active (under control of various bacteria which use NO_3^- in water saturated soils after rainfall) in humid tropical soils, and can rival leaching as a cause of N loss (Robertson, 2000). It is especially important in poorly drained soils, but also occurs within soil aggregates and in decomposing plant litter. In unsaturated soils, C availability is the main limiting factor.

Except possibly in N rich krasnozem soils, it is in the manager's interest to limit denitrification in avocado orchard soils. Unfortunately there are very few measurements available of denitrification losses from South African soils. Savanna studies show that NO losses are some 12 times more than $N_2O + NO_2$ losses. Woghiren (2002) estimated NO emissions in savanna granite soils near Skukuza at 2.1 – 2.7 kg $N.ha^{-1}an^{-1}$. Orchard losses would be considerably higher.

Volatilization of NH_3

Ammonia gas (NH_3) is the first inorganic N form released during mineralization. However, NH_3 is converted to NH_4^+ (the ammonium ion) in acid soils and soils with a pH of < 8.0. NH_4^+ is attracted to negatively charged clay and organic matter colloidal particles. Here it is protected from leaching and from volatilization loss as NH_3.

Volatilization losses of NH_3 are significant where soil pH is >8.0 (unlikely in South African avocado soils). However, nearby intensive animal feedlots etc. can result in high NH_3 volatilization, and atmospheric deposition on adjacent landscapes can be 40-50 kg $N.ha^{-1}an^{-1}$, which is certainly important to fruit growers. Near Skukuza, modeled estimates of volatilization were 5.0 – 5.5 kg $N.ha^{-1}an^{-1}$ (Woghiren, 2002; Scholes *et al*., 2003).

N BUDGET IN AVOCADO ORCHARDS

We have given a broad discussion of reactive N inputs (gains) and outputs (losses) from orchard soils. The balance between them constitutes the available N budget, and clearly this differs widely. Unfortunately, few measurements have been made of N pool sizes in plant and / or soil in South African avocado orchards – those of Witney *et al*. (1990) and Stassen *et al*. (1997) are a partial first approximation at best. Even for natural ecosystems, data are scarce. Total soil N values for southern African savannas, for example, range from 3 060 to 4 635 kg $N.ha^{-1}$, while plant available N pools are 182 to 300 kg $N.ha^{-1}$. Total stock of N on granitic soils near Skukuza was ca 3.7 t ha^{-1} at a nutrient-poor site, and 5.0 t ha^{-1} at a nutrient-rich bottomland site (N in biomass, litter, and soil) (Scholes *et al*., 2003).

It is, however, possible to characterize South

African avocado orchard soils into three broad groups in relation to N pools, and management implications, *viz*.:-

- Potentially "N-saturated" soils (humic oxisols or "krasnozems" on basic rocks [diabase or dolerite])
- Soils with moderate N deficiency (oxisols on granitic, sandstone or shale parent materials; moderate clay and SOM)
- Soils with severe N deficiency (sandy granitic soils with <10-15% clay and very low in SOM).

Since the sizes of the pools in terms of inputs and outputs are virtually unknown, orchard management relies on leaf (and fruit) N content, with supplementary information on soil clay and SOM, and degree of environmental stress (potential tree vigour), helping to fine-tune management recommendations.

MANAGEMENT OPTIONS FOR "N-SATURATED" SOILS

As noted, these are red, heavy clay soils (typically >40%) high in SOM (typically >4% O.M. in top 20 cm), derived from basic rocks such as diabase (Mpumalanga and Limpopo) or dolerite (KwaZulu-Natal) under high rainfall conditions in stable landscapes. They are naturally more fertile than soils derived from granitic, shale or sandstone rocks, the prime N input coming from mineralization of SOM (perhaps in the range 75 to 150 kg $N.ha^{-1}an^{-1}$). In avocado areas in the Mpumalanga escarpment foothill spurs in the Kiepersol / Burgershall, Sabie, White River, and higher-lying terrain near Nelspruit, these soils also receive substantial inputs of N and S from both wet and dry deposition from highveld power stations, perhaps in the order of 20 to 40 kg $N.ha^{-1}an^{-1}$. Inputs of N and S in the middle Elands and Crocodile river valley from the Ngodwana pulp and paper mill are not known by the author.

Aggravating factors contributing to high levels of available N in these soils can be a previous history of banana cultivation, as well as intensive animal operations (past or present, on-site or nearby), or use of virgin soils under grassland (i.e. a short history of soil tillage). A mesic, low-stress climate (potential evapotranspiration and rainfall totals not substantially different; high humidity and cloudiness during rainy season) contributes to potentially high tree vigour, as does any form of tree pruning. N fertilizers, inputs of low C : N ratio organic manures, and legumes (cover crops, cash crops, leguminous "weeds") will all add to the already high available (and potential) N pools. What management options are available to growers in this situation?

- Stop or reduce N fertilization until leaf N falls within the optimum range for the cultivar, rootstock, management philosophy and time of leaf sampling (spring flush in March vs summer flush in May).
- Thoroughly till and water soils before planting, to speed up SOM mineralization and reduce SOM content in the uppermost layer.
- Do not till soils in established orchards, as this releases available N from the N temporarily immobilized in SOM.
- Once the toxic, soluble Al content has been reduced by liming to an acceptable level, reduce the amount and frequency of liming (which speeds up SOM mineralization).
- Apply mulches with a low N and high C content to help "mop up" excess available N. Generally, mulches with C/N ratios of <20 or N contents >1.5% result in net N mineralization, i.e. net release of available N to the soil pool. Mulches with C/N ratios >30 or N contents <1.5% tend to immobilize soil inorganic N (Tisdale *et al*., 1993). Paul & Clark (1996) however point out that mulches with high lignin contents decay very slowly, and may mineralize N at C/N ratios up to 50. Speed of decomposition depends not only on the relative woodiness of the material, but also on its contact with the soil decomposer micro-organisms. The natural dead leaf mulch under healthy avocado trees decays slowly not only because of low N content (N "salvage operation" by the tree before leaf drop), but also because it has poor contact with the soil. Incorporation of mulches would speed up decomposition, but would cut feeder roots.
- Allow woody weeds and grasses (especially stalky grasses) to help "mop up" excess N during the wet season. If space permits, oats and dwarf teff would achieve the same effect. However, competition with the trees for water and nutrients must be countered by increased irrigation (if required), and perhaps fertilization (based on leaf analysis).
- Do not grow legumes as cover or cash crops.
- Chip or mulch prunings with a suitable machine, and spread this useful organic matter in the tree rooting zone. High C : N ratio is the key, i.e. woody material. There may be a case for removing avocado leaves from the orchard, as green leaves have >1.5% N and are net contributors of available N. However, this may be impractical, and from the viewpoint of "sustainable agriculture" it could be argued that any removal of organic matter from an orchard is a criminal act.

- Consider growth retardant sprays (Sunny® or Cultar®).

The above assumes that Phytophthora root rot is under commercial control. This is always the first priority – it is pointless adjusting management practices for high yield and good fruit quality if trees are severely debilitated, C starved, and deficient in feeder roots.

MANAGEMENT OF SEVERELY N-DEFICIENT SOILS

Such soils are likely to have low clay and SOM contents. They are derived from granitic or sandstone parent materials. In avocado areas, the former are typical of the Crocodile river valley near Nelspruit, where rainfall is lower and the environment more stressful (larger difference between potential evapotranspiration and rainfall). In the KwaZulu-Natal midlands, Natal Group Sandstone (formerly Table Mountain Sandstone) and Vryheid Sandstones (formerly Middle Ecca Sandstone) also give rise to sandy, low SOM soils. However, in mistbelt environments on stable, ancient plateaus, the topsoil can be humic (very high SOM), with moderate subsoil clay content of ca 30% – 35% (Anon., 1999). Here we discuss only the sandy soils.

The key features of these sandy soils are their low storage ability for both water and nutrients. They are therefore droughty and stressful to plant roots, with greater temperature fluctuations, and very subject to erosion if not protected by vegetation. They require careful management. They do, however, offer some advantages for tree crops where control of tree vigour is critical (avocado, mango, litchi); and where cultivars more tolerant of stress are grown. In the first category are vigorous cultivars such as 'Fuerte' (and 'Sharwil' in Australia), and 'Pinkerton' (to reduce internal fruit disorders); in the second category are 'Fuerte' and 'Pinkerton' (as opposed to 'Hass' and 'Ryan' avocado).

- In contrast to high clay / high SOM soils, sandy soils require relatively high N inputs. The "little and often" approach is essential – heavy applications are far more subject to leaching and other losses. These soils are ideally suited to fertigation, through which timing can be controlled according to phenological growth stages (Whiley *et al*., 1988).
- Every attempt must be made to build up SOM content – both to improve soil storage ability for water (water holding capacity) and nutrients (cation exchange capacity), as well as to stimulate soil micro-organism activity (a "living" soil). Organic fertilizers offer advantages in these respects, subject to the disadvantage of "slow release" available N not necessarily being timed appropriately to tree needs. Low C / N ratio mulches, especially with a C : N ratio lower than 20, and N content of >1.5%, are called for – in effect they are also organic fertilizers. Legume cover or cash crops in the early years would be encouraged. Tree prunings would be regarded as a welcome source of both short- and long-term available N (and other nutrients), especially after mechanical chipping or mulching, as long as their "hijacking" of N (N negative period or draw-down) is compensated by additional N inputs (based on leaf analysis).

OTHER ASPECTS OF N FERTILIZATION

Type and time of leaf sampling

In spring flush leaves, most commonly used in leaf analysis and sampled some 7 months later in March (S. hemisphere), N concentration increases for 3 to 4 months and then declines, especially during flowering in over-wintered, photo-inhibited leaves about 10 months old (Whiley, 1994). Summer flush leaves, preferred in Australia as they are next season's flowering shoots, have higher N concentration in autumn and winter, and when sampled in April or May (Lahav & Whiley, 2002). These differences must be borne in mind when interpreting leaf analysis results.

Critical N leaf levels

The target range for leaf N concentration is affected by many variables, discussed in detail by Lahav & Whiley (2002). Thus the commercial range world-wide is 1.6% – 2.8% N, but for any specific set of circumstances a much narrower range will be used. For example, the vigorous 'Fuerte' range is usually lower (e.g. 1.6% – 2.0%) than that used for 'Hass' (e.g. 2.2% – 2.6%), where a large leaf surface is needed for reasonable fruit size. Rootstock effects on leaf composition are significant, with Mexican stocks causing higher leaf N than Guatemalan and West Indian stocks (Lahav & Whiley, 2002). High leaf N is less invigorating in cold climates than in warm, forcing environments; and better tolerated on sandy as opposed to clayey, high SOM soils. Site specific N recommendations make for more scientific orchard management.

Timing of N fertilization

A wide range of philosophies apply due to major differences between summer and winter rainfall areas, management practices, pruning techniques and site specific conditions. Whiley *et al*. (1988) used a phenological growth model to guide orchard management, and concluded that the summer rather than the spring flush should receive the bulk of N applied. This was later reinforced by the pheno-physiological growth model (Whiley, 1994; Whiley *et al*., 1998), which notes severe chlorophyll decline and photoinhibition of overwintered leaves, and the benefit of a leaf N boost before flowering provided that vigour is reduced by a growth retardant.

Timing of N fertilization is reviewed by Lahav & Whiley (2002). Two over-riding principles apply. The first is that excessive tree vigour is antagonistic to fruit set and yield, as the spring growth flush may then occur too early and grow too vigorously, and compete with setting fruits during the "sink" phase of shoot growth (Whiley, 1994). Furthermore, in the age of high density planting and tree pruning, excess vegetative growth is inimical and counter-productive to the ideal of smaller trees. The danger of excessive growth is higher in the humid, warm, mesic subtropics than in semi-arid and winter rainfall climates. The second principle is that healthy, photosynthetically efficient overwintered leaves are needed during fruit set, especially in the humid subtropics where less storage starch is accumulated to help fuel fruit set.

Lovatt (2001) has shown benefits from late summer / autumn applications of N in semi-arid winter-rainfall environments. Here overwintered leaves are likely to be more severely stressed, aggravated by salinity, cold and wet soils in winter (less N uptake), and carryover effects of the stressful summer.

Usefulness of strategic foliar sprays

As N is a macro-element, one or two foliar sprays of N compounds will only supply a small proportion of the tree's annual needs (unlike micro-elements, where a single spray will usually suffice). Nevertheless, there are situations when it is appropriate to quickly supply small amounts of N to boost leaf condition. An example is a tree recovering from Phytophthora root rot; improving the efficiency and longevity of photoinhibited overwintered leaves is another. One or two sprays (2 to 3 weeks apart) of low biuret urea (1% concentration) can help rejuvenate "tired" trees (after other appropriate corrective treatment) and encourage vegetative shoot flushes. Several other N containing compounds can be used.

N interactions with other nutrients

The danger of a limited review is that the importance of other elements, as well as nutrient balances and interactions, are not discussed. Lahav & Whiley (2002) summarize the effects of N, P and K on other elements in leaves. Application of N *increases* leaf N, P, Mn, and Fe; *decreases* leaf Zn, B and Cl^-; has no effect or decreases leaf K; and may or may not affect leaf Ca, Mg and Cu. Similarly, effects may be expected on *fruit* flesh levels – being researched worldwide and especially by Hofman and co-workers in Australia, e.g. Marques *et. al.* (2003).

N and fruit quality

It is now accepted that high fruit flesh N content is associated with several fruit physiological disorders, usually in association with low Ca and perhaps levels of other nutrients such as K and Mg, and B. 'Pinkerton' is known to be more sensitive to fruit quality disorders, so that SAAGA initiated specific research on this cultivar in 1999. High risk areas for 'Pinkerton' fruit quality problems have fertile soils high in organic matter, and occur in high rainfall, warm but mesic areas conducive to vigorous growth; low risk areas have sandier, less fertile soils in more stressful environments (Kruger *et al*., 2000).

High soil nitrogen levels increase fruit flesh N, causing faster ripening and more internal disorders (Arpaia *et al.,* 1996), and are positively correlated with flesh discolouration in 'Fuerte' (Koen *et al*., 1990) and 'Pinkerton' (Kruger *et al*., 2001; Van Rooyen & Bower, 2003). Kruger *et al*. (2000, 2001) and Snijder *et al*. (2002, 2003) have proposed and refined 'Pinkerton' export parameters, including flesh N content (in both high risk "off crop" and low risk "on crop" seasons). Other cultivars experience similar but less pronounced quality problems. Further refinements are likely, but fruit flesh N content for 'Fuerte', 'Hass' and 'Pinkerton' produced in the Tzaneen, Kiepersol and Nelspruit areas should not exceed 1.7% during November (Snijder *et al*., 2003). A 'Pinkerton' fruit flesh N level below 1.0% by March will control grey pulp, but for reduction of black cold, this level should be reached by January (Snijder *et al*., 2002). Fruit from low risk areas is likely to have <1.0% flesh N most of the fruit growing period. While a high flesh Ca content is helpful and raises the Ca:N ratio, flesh N content is more important in determining fruit storage potential.

Practical implications of the above emphasis on reducing fruit flesh N concentration, relate to the previous discussion on managing high SOM soils. 'Pinkerton' and 'Fuerte', in the author's experience, are best grown on less fertile, low SOM soils, where it is easier to manage tree and fruit N levels and tree vigour. Such areas need not necessarily be cool – seemingly, N status over-rides temperature. This is shown by successful 'Pinkerton' orchards on very sandy, droughty soils with <10% topsoil clay near Nelspruit, and on sandstone-derived soils (even with humic A horizons) in KwaZulu-Natal, provided N nutrition is correctly managed.

RESEARCH NEEDS

N fertilization strategies for avocado have traditionally relied on once-yearly leaf analysis, as data from soil analyses of plant available N are meaningless. The leaf is thus used as the key integrator of all the complex processes affecting N nutrition. That this is insufficient, even if educated guesses have been made as to the specific target N range for a particular combination of cultivar, rootstock, soil type, climate and management philosophy, is shown by mistakes made and expensive lessons learnt in the last decade. Low yield and poor fruit quality have been consequences of this pragmatic "learn from experience" era.

Perhaps the most important lesson has been the role of soil type, especially clay and organic matter content. This reinforces the notion that each farm represents a specific set of circumstances, so that site-specific fertilization strategies are imperative. Field fertilization trials (e.g. Koen & Du Plessis, 1991; Du Plessis *et al*., 1988) can at best set broad guidelines. Research on the role of N nutrition on fruit quality has been very helpful. N fertilizer trials may show yield increases, but often also yield decreases due to over-invigoration. On a global basis, N fertilizer rates vary from zero to 200 kg $N.ha^{-1}an^{-1}$, and even ca 400 kg $N.ha^{-1}an^{-1}$ for a particular orchard management philosophy (high N combined with pruning and Sunny® applications) being trialled in Israel (Hofshi, 1996).

I believe that research on N budgets and cycling in South African avocado orchards would improve our ability to make rational management decisions. Ideally, the three varying orchard environments should be compared, *viz*.:-

- High clay / high SOM orchards
- Typical red loamy Hutton soils (intermediate clay and SOM)
- Sandy soils with <15% clay and low SOM.

There is also a need to fine-tune leaf analysis standards for cultivar, rootstock, pruning regimes and orchard floor management systems. Effects on fruit quality, and interactions with other nutrients, must also be incorporated. It is an indictment of intensive horticulture that N cycling is better understood in South African savanna ecosystems, forestry areas, and non-intensive agronomic and animal systems than it is in orchards.

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