Royal
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# AN INVESTIGATIVE SOIL HEALTH ANALYSIS OF AVOCADO ORCHARDS IN EASTERN ZIMBABWE

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This Dissertation is submitted in part fulfilment of the requirements for the BSc (Hons) Agriculture of the Royal Agricultural University, Cirencester, 2022.

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# Abstract

Avocado Production in Zimbabwe is facing the challenges of soil degradation, driven by climate change and damaging cultivation practices. Depleted soil health influences soil structure, nutrient cycling, hydrologic processes, and microbial activity, this is reflected in tree development during important phenological stages and encourages the contraction of *Phytophthora* root rot, it was recognised that the key soil health indicators are an integration of physical, chemical, and biological factors. This study tested for the performance of soil health indicators over time, on 7 commercial avocado fields in Chipinge, split into 3 age groups respectively (new, mid, and old). The 8 aspects tested in the avocado rooting zone for, were SOM%, bulk density, pH, nutrient status, EC, SM%, VESS score and earthworm counts. The distribution of results was contradictive to the hypothesis and showed there was a significant improvement in all the key performance indicators over time, with new fields having the weakest soil health and the old fields having the strongest soil health. The evaluation recognised important relationships between SOM% and soil health, suggestions were made to increase overall soil health with organic materials requires management techniques such as mixed cover cropping, mulching, and liming.

**Key words** – Avocado, bulk density, Hass avocado, Soil health, Soil organic matter, Phytophthora, Zimbabwe.

# Acknowledgements

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# Abbreviations

**AEC** – Anion Exchange Capacity

**Ca** – Calcium

**CEC** – Cation Exchange Capacity

**EC** – Electrical Conductivity

**FAO** – Food and Agriculture Organization

**Fe** – Iron

**K** – Potassium

**Mg** – Magnesium

**Mn** – Manganese

**N** – Nitrogen

**Na** – Sodium

**P** – Phosphorus

**SH** – soil health

**SM** – Soil Moisture

**SOC** – Soil Organic Carbon

**SOM** – soil organic matter

**VESS** – Visual Evaluation of Soil Structure

**Zn** - Zinc

# 1. Introduction

## 1.1 Background

The Avocado *(Persea americana)* has seen a global upward trend in its demand on the international fruit market, the interest in the aptly named "superfood" is driven by its incredible healthy qualities. The fruit has a high nutrient-density which is popular among health-conscious buyers, consisting of essential nutrients like, Vitamin (A, B, C, E and K), omega, phytochemicals, antioxidants, fibre, and minerals (Mg and K) (Rodriguez, 2021).

The increasing worldwide demand for the Avocado superfood, has seen an exponential increase in its cultivation all over the globe, (Rodriguez P. , 2020), this has led to positive and negative effects on the 3 pillars of sustainability in the commercial avocado production sector (Purvis, Mao, & Robinson, 2019), namely: Economic, Environmental and Social. The industry has given the opportunity to address food security issues in many areas, allowing growers in suitable areas to diversify and target external markets for foreign currency. The prospect for growing export markets, has provided an opportunity for farmers in the eastern highlands such as Chipinge in Eastern Zimbabwe to benefit from the upsurge in demand in global markets (McCauley, 2020).

Increase in demand has led to an increase in intensive production, which has led to deforestation of large areas, in turn damaging local ecosystems, biodiversity loss and soil degradation (Bravo-Espinosa, Mendoza, Carlon Allende, Saenz-Reyes, & Paez, 2014). The damage has been caused by erosion, salinization, nutrient depletion, acidification, and production enhancing inputs (Lal, 2015).

Since 2018, Zimbabwe has been exporting more than 5000 tonnes of Avocados to international markets (Zimbabwe Avocados Market Insights, 2021), the fruit is an important economic component in the country but is facing many challenges that are hindering its production, from climate change, political influence and most importantly soil degradation. It is important for the producers in the avocado sector to enhance the sustainability of the soil resource to ensure consistent production in the future, by improving or maintaining the key soil qualities (1) physical structure, (2) chemical components and (3) biological processes (Lal, 2015). Soil function is an important aspect and the integration of its processes: (fertility, nutrient cycling, carbon storage, hydrological processes, and biological activity) provide ecosystem services for producing crops and local flora and fauna (Vogel, et al., 2019).

It is important to understand the effects of crop management practices on our soils, the impacts on soil characteristics like soil organic matter (SOM), having long term consequences and equate to loss in production. Gaining an understanding on where soil depletion occurs in an avocado orchard will provide a basis to address these problems.

The main objective of this research paper is to assess soil properties for 3 different stages of production in commercial avocado setups in Chipinge, Eastern Zimbabwe, and identify the key processes that account for depleting soil qualities and their relationship with the overall soil health (SH). The process of data capture and handling will be followed by suggestions for sustainable soil management practices that can be implemented to reverse, maintain, or improve the overall soil health of plantations at various production stages, possibly creating conditions like the origin of the avocado.

## 1.2 Rationale

The tree cropping industry in Zimbabwe whether small or large scale, is facing challenges in the form of soil degradation. More frequent occurrences of leaching, erosion, and nutrient depletion, that are damaging soil qualities are a concern for many avocado farmers in the area like myself, these are caused by unpredictable weather events, mismanagement of soils from cultivation practices, limited range of beneficial inputs and the conversion of exhausted arable fields into plantations. This gives the opportunity to assess the damaging factors by investigating soil quality defects to a higher degree, farmers will gain a deeper understanding of sustainable soil management relevant to tree cropping specifically. The knowledge gained will be crucial in integrating soil regenerative techniques into the avocado industry, reducing the effects of soil degradation, ensuring consistent crop yields, and improving resource management.

## 1.3 Research Aims and Objectives

### 1.3.1 Research Question

Are there any significant impacts of commercial avocado production practices on the main soil health characteristics?.

### 1.3.2 Research Objectives

The aim of this study is to test and analyse the key soil health indicators of avocado orchards, analyse the results to see whether practices are degrading soil quality.

- Critically analyse key soil health indicators and compare findings for the different aged avocado orchards.
- Assess data to see how different soil attributes influence each other.
- Suggest possible improvements in sustainable soil health management techniques.

### 1.3.3 Hypothesis

Avocado cultivation has significant negative impacts on soil health and contributes to soil degradation.

# 2. Chapter 1: Literature Review

## 2.1 Avocado Production

### 2.1.1 Global production

The avocado market is one of the fastest expanding markets worldwide, in recent decades it has been driven by a combination of socio-economic and marketing factors, mainly its association with various health benefits (Bhore, et al., 2021). This had led to an increase in global cultivation of the fruit, with 63 countries producing avocados on a commercial scale, with the majority of largest producer's coming from South America, Mexico contributes to 35% of the worlds production followed by the Dominican Republic, Peru, Indonesia, and Colombia (Atlas Big, 2018). Figure 1 below shows the distribution of avocado producing countries, including Zimbabwe. Figure 2 below shows the value of the global avocado market in 2022 at US$15.15Bn and its predicted growth until 2025.

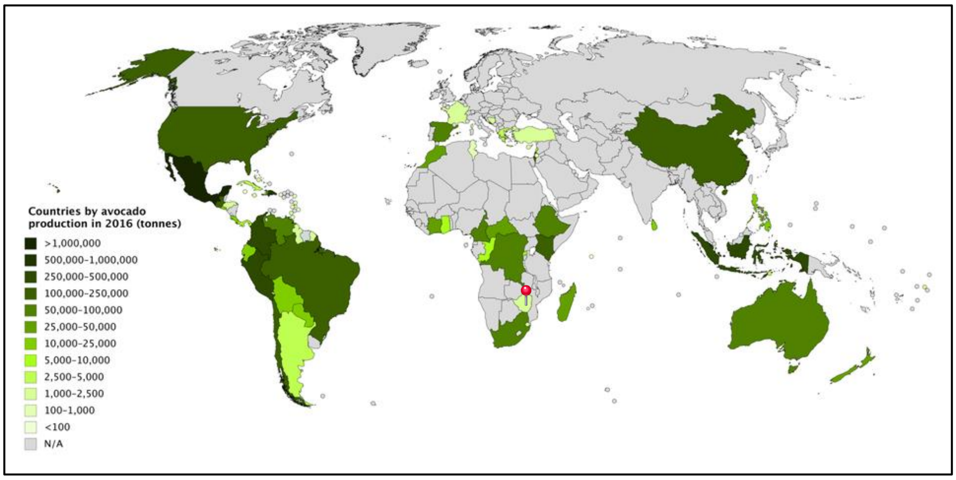


*Figure 1: Avocado Production by Country (FAO, Avocado production by country, 2018)*

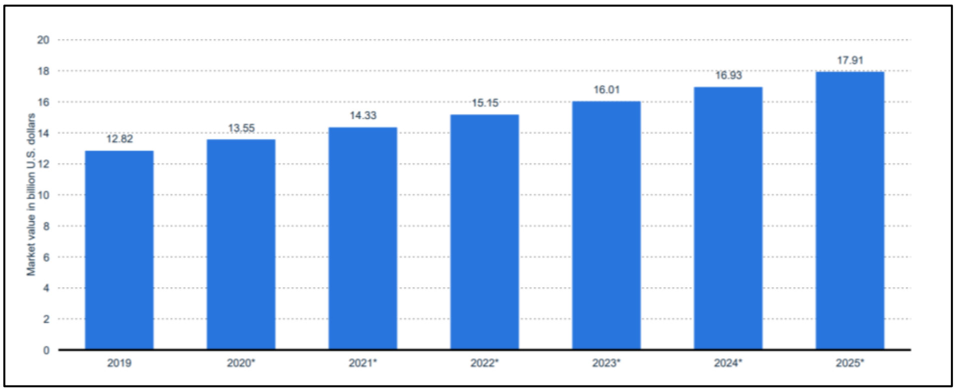


*Figure 2: Value of Avocado market worldwide in Billion US$ (FAO, Avocado industry, 2021)*

The cultivation of the avocado has enormous potential to improve local and national economy, increase agriculture related employment and address food security issues in many areas (Bhore, et al., 2021). However its production criticized and is associated with many implications on the environment and socio-economic related conflict, Mexico's industry has been referred to as "blood avocados", where the cartels control the trade of avocados using "avocado tax", violating the rights of local farmers (Smith L. , 2018). The intensive production of avocados, relating to the use of large areas of cultivated land, high water utilisation, with production enhancing inputs like fertilizers and pesticides has led to various negative impacts on the environment: largescale deforestation for plantations, biodiversity loss from chemicals, water and soil pollution, soil degradation (Ayala, 2020).

The global industry is facing challenges from climate change, with the increases in temperatures, changes in rainfall patterns, changing soil fertility and increasing soil salinity, these factors are concerning the sustainability of production systems (Mukhopadhyay, Sarkar, Jat, Sharma, & Bolan, 2021). McGrath (2022) quoted “The key message for those that are in the main producing regions today is that farming systems have to adapt to the changing conditions”, It is important to understand that avocado producers worldwide are facing very similar challenges, the implications from their own cultivation styles and external factors, making it difficult to produce fruit in a regenerative manner.

A report from Australia (Climate Change risks and opportunities for the avocado industry, 2005) highlights the concerns that arise in the industry from changing climatic conditions on avocado growth and development, from small diurnal temperature range that can potentially impact stages of male and female flower parts and reduces the chances of pollination, temperature increase can shift the warmer growing regions towards cooler areas, Fruit set and maturity will also be affected by temperature increase leading to a shift in harvest times (Deuter, Howden, & Newett, 2005). Higher temperatures are driving more active pest insect populations and the main avocado disease, water mould or root rot, caused by a soilborne oomycete *(Phytophthora cinnamomi)*, will be active for longer periods during the year (Deuter, Howden, & Newett, 2005).

The industry is also facing the challenge of climate related soil degradation, soils are interconnected to the atmosphere through the carbon and nitrogen cycles and hydrologic processes (Brevik, 2013). Brevik (2013) reported that soils may become a net source of atmospheric carbon, lowering the SOM levels in the soil, weakening the potential for crop growth and higher frequency of soil erosion. A report from (Garcia-Fayos & Bochet, 2008) found strong correlations between climate change and soil erosion, negative impacts on aggregate stability, bulk density, water holding capacity, Ph, SOM content, total N, and soluble P in the soil, all the properties that are important for soil health and crop growth.

### 2.1.2 Avocado production in Zimbabwe

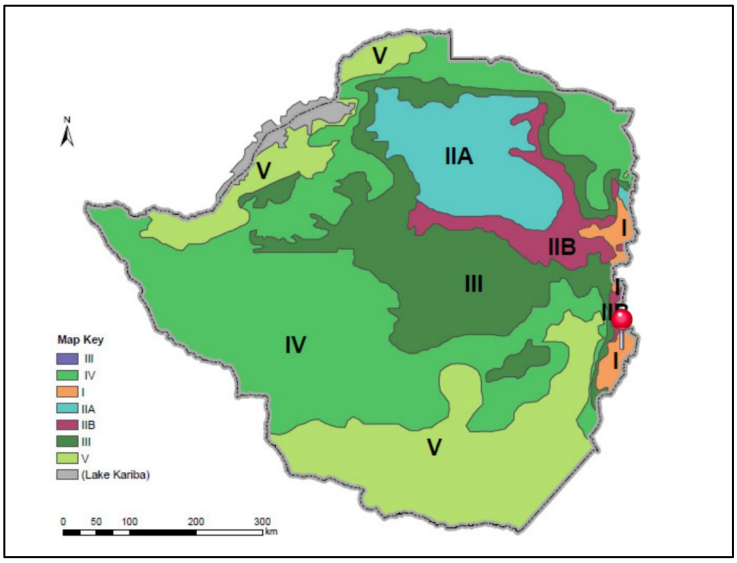


*Figure 3: Agro-ecological regions of Zimbabwe (Kashangura, 2014)*

Suitable climatic conditions in natural region 1 in Zimbabwe as shown in figure 3 above, has seen the cultivation of export quality avocados in the country, the movement toward avocados started in the late 1980’s, where farmers and corporates diversified into other export crops like the avocado and macadamia nut from coffee and tea-oriented systems (Sibanda, 2022). Avocados are commercially grown in the Eastern highlands of Zimbabwe, comprising of Small-scale and large-scale Avocado production systems, the small-scale systems support local markets and rural livelihoods with a small economic value, large-scale systems produce export quality fruit and in some cases supply to local supermarkets and fresh produce stores, they have a high output and economic significance (Majuru, 2021). Figure 4, below shows the primary avocado producing region in Zimbabwe, centred mainly around the Chipinge town in the Eastern Highlands.

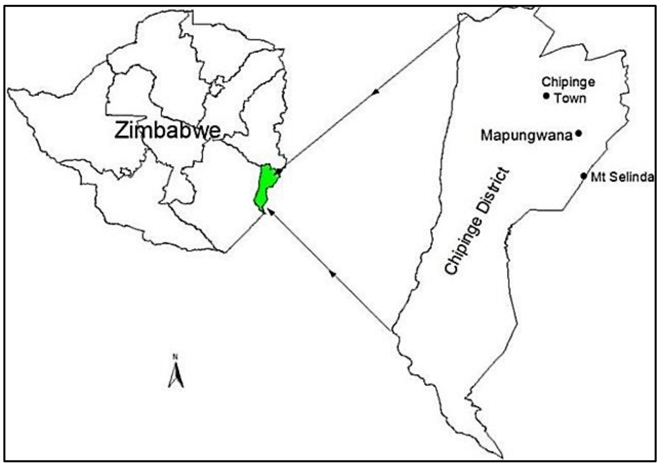


*Figure 4: location of Chipinge, the main avocado producing area in Zimbabwe (Matikiti, Chigonda, & Rusena, 2018)*

The commercial avocado sector in Zimbabwe is certified under GLOBAL G.A.P, which covers all stages of production and ensures compliance to food health and safety standards. Producers cultivate the preferred and globally recognized avocado variety called HASS, because of its advantages in consistent high yielding, good fruit quality and exceptional hardiness in long distance transport (Faber, 2016). Producers are exploiting the international markets in Europe and the United Kingdom, with the main consumer being the Netherlands, acquiring up to 70% of the avocados produced (African Harvesters, 2017). Zimbabwe is in the top 5 exporters of Avocados in Africa, with the sector being valued at US$14.1 million (Zimbabwe Avocados Market Insights, 2021). It is a very important growing sector for agriculture in Zimbabwe, with a significant economic influence. Figure 5 below shows the growth of production, value in tonnes of avocados exported annually until 2019, with current figures sitting at 8500 tonnes per annum.

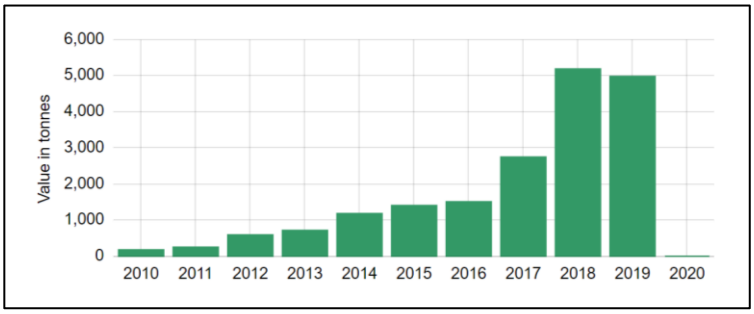


*Figure 5: Zimbabwe's Avocado Exports (Zimbabwe Avocados Market Insights, 2021)*

With an estimated area of 1250 Ha under avocado cultivation (Zimbabwe Avocados Market Insights, 2021), producers in Chipinge follow a universal cultivation technique illustrated in Figure 6 below the

PEGG wheel designed in Australia, with an element of adaptation to the local challenges. Some of the challenges faced in the local industry are root suffocation from soil moisture saturation which can also cause the contraction of root rot from *P. cinnamomi*, Environmental factors like frost and sunburn, pests and diseases: Leaf rolling caterpillars (*Tortrix* and *Amorbia*), stem canker (*Botryosphaeria ribis*), Fruit fly, Mealy bug, Coconut bug and sun blotch viroid (Department of Agriculture, Forestry and Fisheries, 2012).

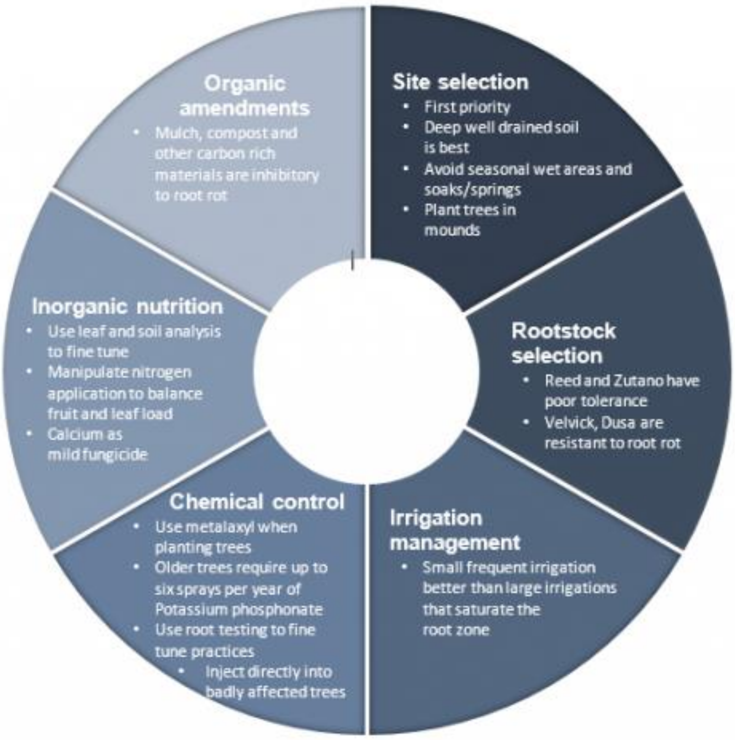
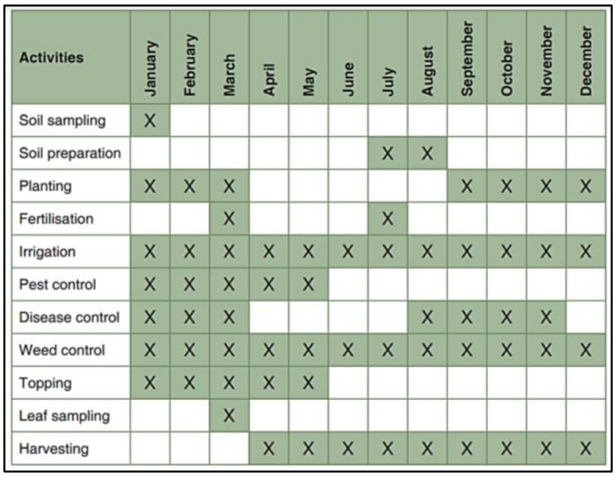


*Figure 6: The PEGG wheel (McCauley, 2020)*

Locally farmers focus on the key factors when developing an orchard: Soil colour, soil quality, ridges and drainage, erosion prone landscapes, tree spacing, quality of cultivar and rootstock varieties and frost-free zones. Field preparation involves large areas of natural vegetation to be cleared or the conversion of arable fields into orchards, continuous mounds known as ridges are constructed with heavy equipment, the importance of mounds in plantations are improving soil drainage and this also reduces the risk of trees contracting *P. cinnamomi* (Grant, 2015). Young trees are planted at 1 year of age, usually trees are obtained from a credible nursery or propagated under professional standards on the farm with sun blotch screened material and will likely bear fruit within 4 to 6 years, with a lifespan of over 50 years (Louw, N.D.). Importantly spacing of trees is focused on early breakeven and reaching optimal production quickly, within a few years the high density planting will have overcrowding and light penetration issues that start to occur and hinder production, but farmers are using pruning and thinning techniques to control tree canopy and branches shown in Table 1 below, exposing the inner parts of the tree, reducing crowding and maximising light interception and distribution (Kohne, 1989).

| Years | Hass variety in High vigour areas |
|---|---|
| 1 to 7-10 | 7mx3.5m (408 trees/Ha) |
| 8-10 to 14 | 7mx7m (204 trees/Ha) |
| 8-14 to 20 | 7mx14m (102 trees/Ha) |

*Table 1: Guideline to spacing and thinning of Orchards (Kohne, 1989).*



| Activities | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soil sampling | X | | | | | | | | | | | |
| Soil preparation | | | | | | | X | X | | | | |
| Planting | X | X | X | | | | | | X | X | X | X |
| Fertilisation | | | X | | | | X | | | | | |
| Irrigation | X | X | X | X | X | X | X | X | X | X | X | X |
| Pest control | X | X | X | X | X | | | | | | | |
| Disease control | X | X | X | | | | | X | X | X | X | |
| Weed control | X | X | X | X | X | X | X | X | X | X | X | X |
| Topping | X | X | X | X | X | | | | | | | |
| Leaf sampling | | | X | | | | | | | | | |
| Harvesting | | | | X | X | X | X | X | X | X | X | X |

*Table 2: Production Schedule (Department of Agriculture, Forestry and Fisheries, 2012).*

Locally Farmers follow an integrated management model as shown above in Table 2, however it varies between farmers because of different farm dynamics. Timings of nutrient application is universal where the seasonal nutrient applications match the crop's nutrient demand during phenological growth stages of the tree's vegetation, flowers, and fruit (Selladurai & Awachare, 2019), as are many of the other activities dependant on phenological stages.

Irrigation of these trees occurs within the rooting zone, basins around trees are a vital part in water capture and retention for younger trees but become of less importance when there is a vegetative canopy. Trees are irrigated with microjets or physically by water cart, at applicable rates every week, depending on soil moisture content and weather conditions.

Zimbabwe's industry is small in comparison to the biggest producers globally, the factors that drive production are similar however farmers do face some unique challenges in this environment. Practical implications in Zimbabwe's monoculture avocados are enhanced by climate change events, challenging the sustainability of natural resources in the area and ultimately production.

Cultivation impacts from ridging can have potential erosion problems on slopes with a gradient higher than 4%, if ridges do not follow the natural contour of the land or are not adequately managed, which is a common concern in Chipinge with uneven topography  (Ditsch, 1986). Field operations during ridging and crop management, can result in severe deep-seated interrow compaction, crusting, reduced soil organic matter, and contributing to soil degradation, with a higher bulk density and reduced aggregate stability causing restricted root development and limited root access to water and nutrients. Compaction is also linked to increasing susceptibility of disease contraction, specifically *P cinnamomi*, and has direct impacts on yield, quality, and production costs (Maskova, Simmons, Deeks, & Baets, 2021).

Nutrient leaching is initiated by hydrologic processes and soil characteristics but is influenced to a higher degree from the farmers cultivation practices such as fertilizer management styles, irrigation practices, crop characteristics and crop management styles. Leached nutrients have a negative impact on the environment and production, loss of nitrates causes soil acidification and essential nutrients are lost below the root zone (Kiggindu, Magliaccio, Schaffer, Li, & Crane, 2012). Leaching of applied or spilled pesticides into local surface and ground water, causing contamination and an unknown scale of damage to biodiversity and water quality in the area (Kellogg, 2000). Spraying large orchards with pesticides, in some situations leads to drift and unintentional contact with local insects and vegetation, damaging populations of beneficial plants, insects and importantly most farmers use beehives to increase production, hindering the efficiency of the pollination process (Sanchez-Bayo & Goka, 2014).

Trees play an important role in sequestering carbon, however management practices like pruning and thinning can result in direct losses of carbon, unless the material is returned to the soil in the form of organic matter (Gomez-munoz, Valero-Velanzuela, Hinojosa, & Garcia-Ruiz, 2016). Some of the orchards in the area have been developed on fields previously used for arable crops, specifically maize, these fields carry degradation factors from years of cultivation. Dechert, Veldkamp and Anas (2004) had reported soil organic matter in maize fields decreases during continuous cultivations, reducing soil fertility.

Various practical implications occur in the plantations and have short term and long-term consequences on the trees, their production, natural flora, and fauna and ultimately the soil. Understanding the importance of a healthy soil is important for achieving long term production goals and maintaining a favourable environment.

### 2.1.3 Plant physiology

The Avocado *(Persea americana)*, a fruit originating from tropical areas in eastern and central Mexico, Guatemala, and central America down to the northern parts of Peru and Ecuador (Silva & Ledesma, 2014). The species has been classified into 3 distinct subspecies (Tovar & Fernandez, 2010):

1) Mexican race - *P americana. Var. Drymifolia*

2) Guatemalan race - *P americana. Var. Guatemalensis*

3) West Indian race - *P americana. Var. Americana*

The three races described above gave rise to the modern commercial cultivars, through methods of crossbreeding and hybridisation, most common commercially produced fruiting varieties: Hass, Fuerte, Gwen, Reed, Ryan, Zutano, and the most common rootstock varieties: Dusa, Duke 7, Latas, Bounty, Zutano, Edranol, West Indian (Schaffer, Wolstenholme, & Whiley, 2013). Locally in Zimbabwe farmers have the commercial fruiting variety Hass, propagated with seedling or clonal rootstock varieties of either, Duke 7, Dusa, Edranol or West Indian. Rootstocks and fruiting varieties are selected by characteristics of resistance to *P cinnamomi*, hybrid vigour, tolerance to temperature fluctuation, and fruiting varieties by market preference and logistical durability. Figure 7, 8, and table 3 below show the fruit characteristics, a mature tree, and nutrient composition of the Hass avocado fruit, respectively.

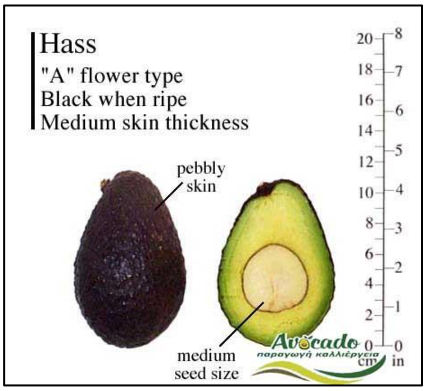
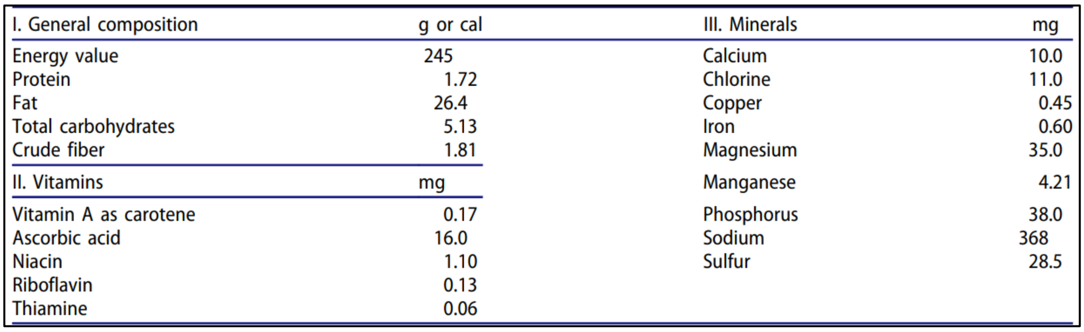


Figure 7: Hass Avocado variety description (Avocado-Hellas, 2021).

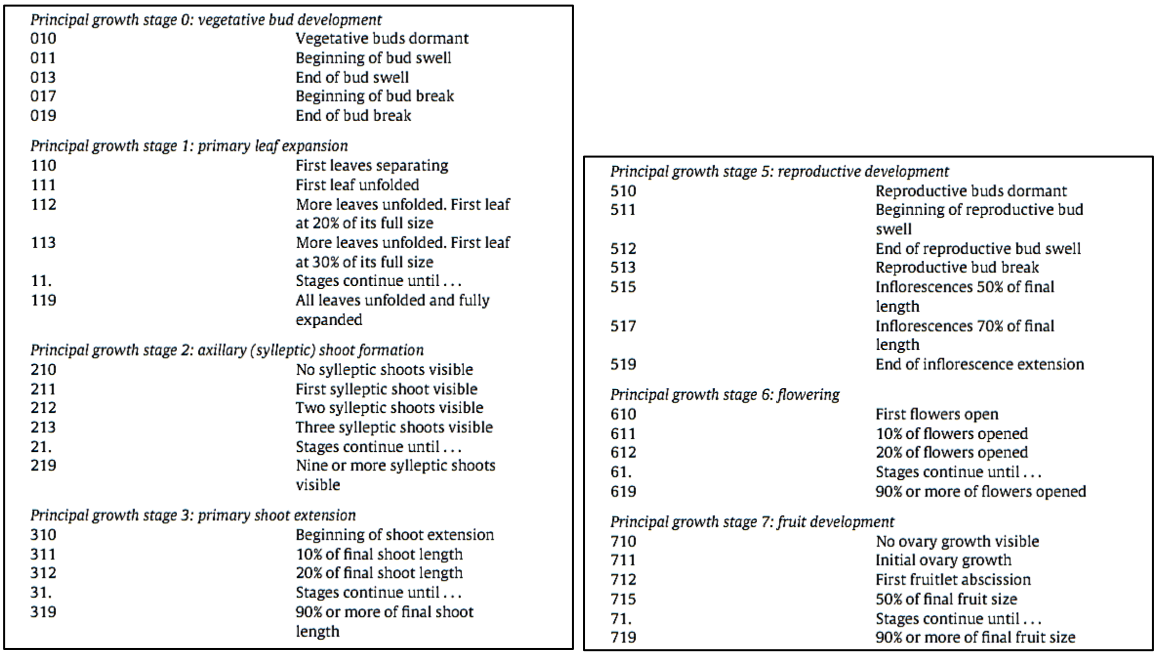
Figure 8: Mature Hass avocado tree



| I. General composition | g or cal | III. Minerals | mg |
|---|---|---|---|
| Energy value | 245 | Calcium | 10.0 |
| Protein | 1.72 | Chlorine | 11.0 |
| Fat | 26.4 | Copper | 0.45 |
| Total carbohydrates | 5.13 | Iron | 0.60 |
| Crude fiber | 1.81 | Magnesium | 35.0 |
| II. Vitamins | mg | Manganese | 4.21 |
| Vitamin A as carotene | 0.17 | Phosphorus | 38.0 |
| Ascorbic acid | 16.0 | Sodium | 368 |
| Niacin | 1.10 | Sulfur | 28.5 |
| Riboflavin | 0.13 | | |
| Thiamine | 0.06 | | |

*Table 3: Chemical composition of Avocado fruit per 100g of edible fruit (Selladurai & Awachare, 2019).*

Avocados exhibit a rhythmic growth pattern, having 2 seasonal vegetative and root flushes and 1 reproductive phase annually (Alcaraz, Thorp, & Hormaza, 2013). There are 7 growth stages that depict the phenological vegetative and reproductive stages, described with a BBCH scale, shown below in Figure 9.



| | |
|---|---|
| *Principal growth stage 0: vegetative bud development* | |
| 010 | Vegetative buds dormant |
| 011 | Beginning of bud swell |
| 013 | End of bud swell |
| 017 | Beginning of bud break |
| 019 | End of bud break |
| *Principal growth stage 1: primary leaf expansion* | |
| 110 | First leaves separating |
| 111 | First leaf unfolded |
| 112 | More leaves unfolded. First leaf at 20% of its full size |
| 113 | More leaves unfolded. First leaf at 30% of its full size |
| 11. | Stages continue until . . . |
| 119 | All leaves unfolded and fully expanded |
| *Principal growth stage 2: axillary (sylleptic) shoot formation* | |
| 210 | No sylleptic shoots visible |
| 211 | First sylleptic shoot visible |
| 212 | Two sylleptic shoots visible |
| 213 | Three sylleptic shoots visible |
| 21. | Stages continue until . . . |
| 219 | Nine or more sylleptic shoots visible |
| *Principal growth stage 3: primary shoot extension* | |
| 310 | Beginning of shoot extension |
| 311 | 10% of final shoot length |
| 312 | 20% of final shoot length |
| 31. | Stages continue until . . . |
| 319 | 90% or more of final shoot length |

| | |
|---|---|
| *Principal growth stage 5: reproductive development* | |
| 510 | Reproductive buds dormant |
| 511 | Beginning of reproductive bud swell |
| 512 | End of reproductive bud swell |
| 513 | Reproductive bud break |
| 515 | Inflorescences 50% of final length |
| 517 | Inflorescences 70% of final length |
| 519 | End of inflorescence extension |
| *Principal growth stage 6: flowering* | |
| 610 | First flowers open |
| 611 | 10% of flowers opened |
| 612 | 20% of flowers opened |
| 61. | Stages continue until . . . |
| 619 | 90% or more of flowers opened |
| *Principal growth stage 7: fruit development* | |
| 710 | No ovary growth visible |
| 711 | Initial ovary growth |
| 712 | First fruitlet abscission |
| 715 | 50% of final fruit size |
| 71. | Stages continue until . . . |
| 719 | 90% or more of final fruit size |

*Figure 9: Description of the phenological growth stages of an avocado (Alcaraz, Thorp, & Hormaza, 2013).*

The growth cycle of an avocado is influenced to a large extent by environmental conditions, but the periodicity of the different phenological growth stages remains predictable, Ploetz, Ramos and Parrado (1992) described the relationship between shoot and root growth to be cyclic, where root growth followed shoot growth after 30-60 days, and suggested these flushes can be used to treat the trees with fungicide against *P cinnamomi*, at the time of maximum root growth where it poses the greatest threat. Figure 10 below shows the cyclic relationships of the phenological stages during the year.

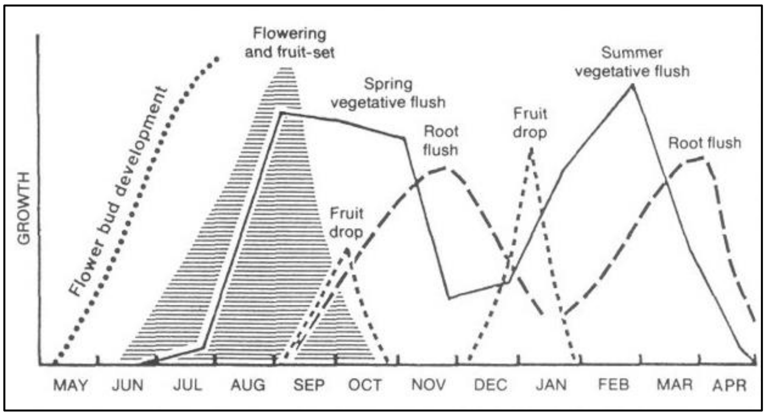
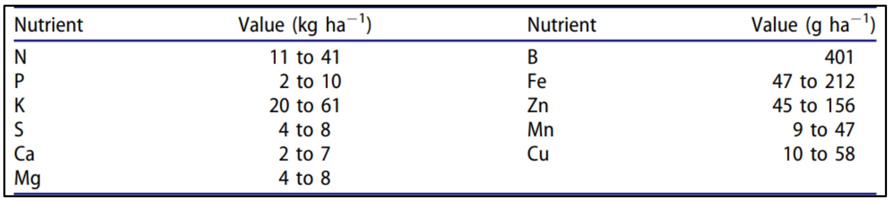


*Figure 10: Phenological growth cycle of Hass Avocado in Southern Africa (Wolstenholme & Whiley, 1989).*

The avocado has a relatively shallow root system with more than 70% of its roots in the upper 0.5m of the soil profile, and can be regarded as a surface feeder/rooting tree. Eliot Coit (1940) quoted "Where mats of these fibrous feeders are permitted to develop normally near and at the surface, they function best when protected by a heavy undisturbed mulch of leaves and are kept reasonably moist", avocado tree roots require access to a lot of air, when root fibers are partially deprived of air from either heavy soil or free water, this results in asphyxiation and depending on the degree of severity it can be shown as discomfort by the tree (Eliot Coit, 1940). Trees that encouter water stress, which is due to lack of water in the soil, may result in fruit drop and loss of yield.

Table 4 below shows the nurient removal of a hass avocado crop.



| Nutrient | Value (kg ha$^{-1}$) | Nutrient | Value (g ha$^{-1}$) |
|---|---|---|---|
| N | 11 to 41 | B | 401 |
| P | 2 to 10 | Fe | 47 to 212 |
| K | 20 to 61 | Zn | 45 to 156 |
| S | 4 to 8 | Mn | 9 to 47 |
| Ca | 2 to 7 | Cu | 10 to 58 |
| Mg | 4 to 8 | | |

*Table 4: Nutrients removed by an Avocado crop based on a 10t/Ha yield (Selladurai & Awachare, 2019).*

## 2.1.4 Soil Requirements for Avocado's

From the beginning many avocados growers looked at climatic suitability for avocado cultivation with water access, and considered soil quality to be of secondary importance, as a result many trees have been planted on unfitting soils. Avocados require specific soils, but can adapt to a certain degree, the preferred soil for production are Andosol soils, with a high OM%, or red to reddish-brown soils with a clay content of 20-40%, the structure and texture that allows for drainage and good nutrient and water holding capacity, but do not restrict root development or lead to oversaturation from excessive water (ARC institute, 2000). Desired soil conditions have a pH between 5 and 7, with ideal pH of 6.5, this has been proven to suppress *P cinnamomi* (Wolstenholme & Sheard, 2011).

*Figure 11: Typical Andosol soil profile (Aber & Wolde-Meskel, 2013).*

Nutrition in the tree is dependant on 17 essential elements, 9 of which a macronutrients namely: Hydrogen (H), Carbon (C), Oxygen (O), Nitrogen (N), Potassium (K), Calcium (Ca), Magnesium (Mg), Phosphorus (P), and Sulphur (S) and the other 8 are micronutrients: Chlorine (Cl), Iron (Fe), Boron (B), Manganese (Mn), Zinc (Zn), Copper (Cu), Molybdenum

(Mo), and Nickel (Ni) (Lovatt, 2013). However avocados have a relatively low nutrient demand, based on (1) low amount of mineral deficiencies in commercial orchards, (2) low nutrient removal that can be supplemented easily and (3) no significant yield increase from addition of N,P, or K in field experiments (Lahav, 1995)

Figure 11 above, shows typical characteristics of an Avocado suited soil, with a large percentage of OM in the upper profile and a reddish-brown colour. Poor soil conditions in an avocado orchard must be fixed to the required nutrient composition, structure, and texture to reduce the presence of *P cinnamomi* in the rooting zones. Moreira and Martins (2005) conducted a study on *P cinnamomi* and quoted that “soils with low fertility and low mineral status particularly phosphorus, seemed to favour infection”.

## 2.2 Importance of Soil in avocado production

### 2.2.1 Key Soil Quality Characteristics

Soil health can be defined as the capacity of a soil to provide an environment for long-term optimum plant growth, while ensuring the health of humans, animals, and the environment (Rayne & Aula, 2020). The quality of a soil is determined by a range of physical, chemical, and biological characteristics, this range of criteria can be used to evaluate soil quality quantitatively (Karlen, Eash, & Unger, 1992). Figure 12 below describes the integration of the soil characteristics and the key factors that determine potential soil health.

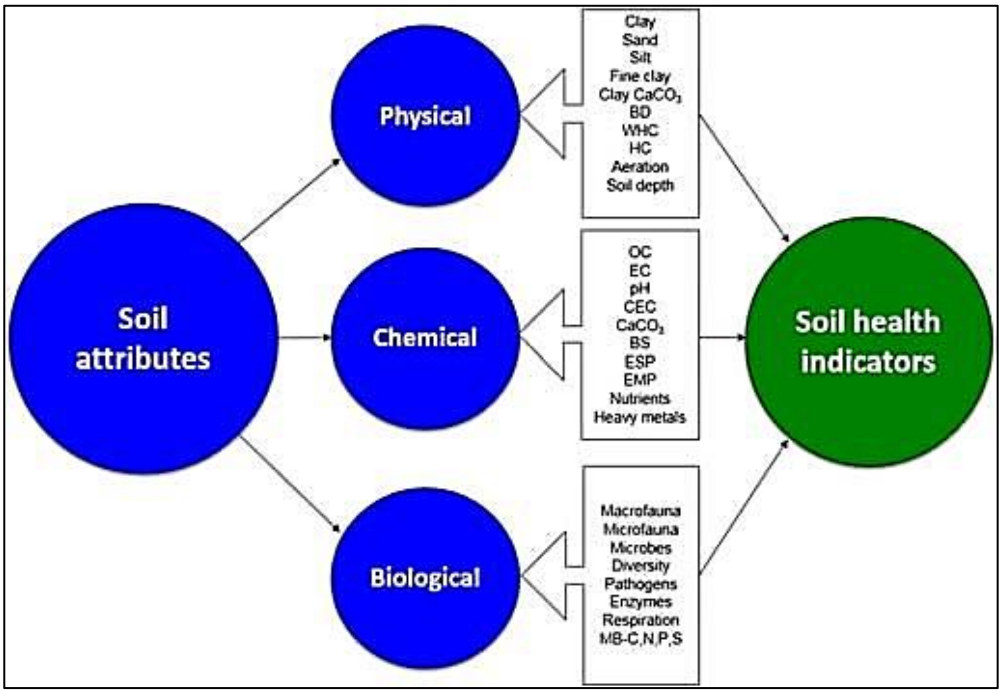


*Figure 12: Soil physical, chemical and biological attributes used as soil health indicators (Velmourougane & Blaise, 2017).*

### 2.2.2 Physical Indicators

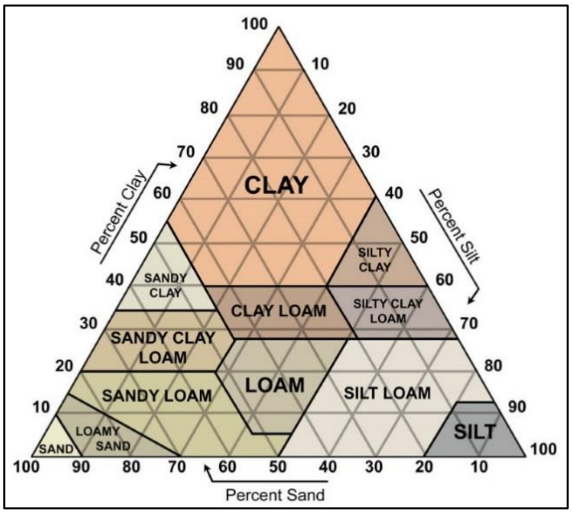


*Figure 13: Soil Texture Triangle (Berry, et al., 2007).*

Soil texture is indicated by the arrangement and ratios of sand, silt, and clay per unit volume of soil as shown on the right in Figure 13. Soil structure is determined by spatial arrangement of particles, aggregates, and pores, a good soil requires higher ratios of large aggregates and a low bulk density. (Bronick & Lal, 2005 ) stated that soil structure and Soil organic carbon (SOC) are interrelated, where SOC is a binding agent for forming soil aggregates, and soil structure is dependent on aggregate stability, highlighting the importance of SOC. (Imadi & Shah, 2016) quoted that "Bulk density of a soil is effectively increased after soils are exposed to organic manure and organic matter for about 5 consecutive years". SOC is lost if SOM is oxidized by decomposers faster than it can be replaced by new biomass (Olson, 2013). Soils with a low bulk density, relating directly to the high porosity facilitate water movement, water holding capacities, gaseous exchange, and nutrient transport (Ramesh T. , et al., 2019). The physical, physico-chemical, and biological activity create a soil structure that plays a key role in determining crop performance, influencing root development and nutrient uptake per unit root length (Marschner & Rengel, 2012)

### 2.2.3 Chemical indicators

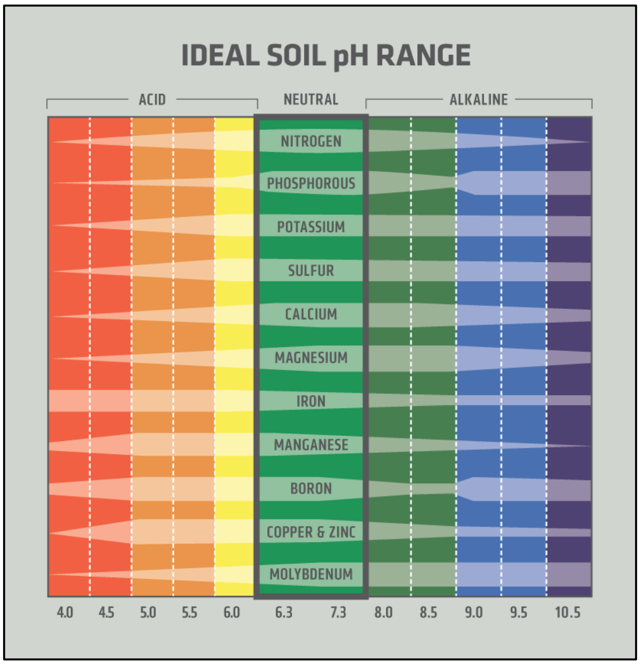


*Figure 14: key nutrients at various pH levels (Jensen & Thomas, 2010).*

Soil chemical properties which include pH, salt concentration/electrical conductivity (EC), cation and anion exchange capacity (CEC and AEC), nutrient status, and organic matter (Kant & Kafkafi, 2013). pH has a large effect on the availability of residual nutrients in the soil and could lead to nutrient deficiencies in trees, as well as availability of applied fertilizers as shown in figure 14 on the right (Jensen & Thomas, 2010). Influence of pH on microbial activity with optimal functions at pH 6-7. CEC is an important factor in the soil, it represents the amount of plant-available nutrients, it plays a key role in buffering changes to soil acidity from nutrient exchange by roots. SOM is the most dynamic soil component and plays an important role in soil processes, has immense impacts on plant yield and growth, acting as a source of slow-release nutrients, it improves the chelation of microelements and buffers soil pH (Reeve, et al., 2016). According to (Reeve, et al., 2016) SOM increases CAC and AEC, which improves plant accessible nutrients and decreases the potential of leaching. SOM provides a substrate for soil microorganisms and fauna, playing a critical role in soil health, this regulates nutrient movement and hydrologic functions and increasing aggregate stability (Hatten & Liles, 2019). Electrical conductivity is used to measure the mobility of charged ions in the soil medium, this reflects how soil porosity and texture influences charged particle movement (Liu, 2015), EC is an indicator of nutrient availability, texture and available water capacity (Husson, Brunet, & Babre, 2018). Soils with an EC of less than 1 dS/m are considered non-saline, within these non-saline soils a higher EC will have a higher nutrient availability (USDA, 2014).

Availability of base cations and micronutrients is influenced by N and available water, where higher rates of N caused lower exchangeable cations of Ca and Mg but higher extractable micronutrients Fe, Mn, and Cu into the soil solution, reducing soil pH (Wang, et al., 2017). Exchangeable Sodium percentage (ESP) was considered by (Laker & Nortje, 2019) to be an important soil factor influencing dispersion and in high levels consequently leading to crusting and reduced water infiltration, different soil types and conditions have differing ESP values, but for red oxic soils with a clay content of 30%, similar to the soils that are under investigation showed ESP values up to 9% had no effect of final infiltration rate (FIR).

The Mulders chart below shows how nutrient concentrations act towards each other, high concentrations of a particular element can act antagonistically or stimulate other elements, as a result this can hinder or increase the plant uptake demand of a certain element. This could in some cases induce plant deficiencies if there is an imbalance in nutrient concentrations in the soil (NutriAg, 2020).

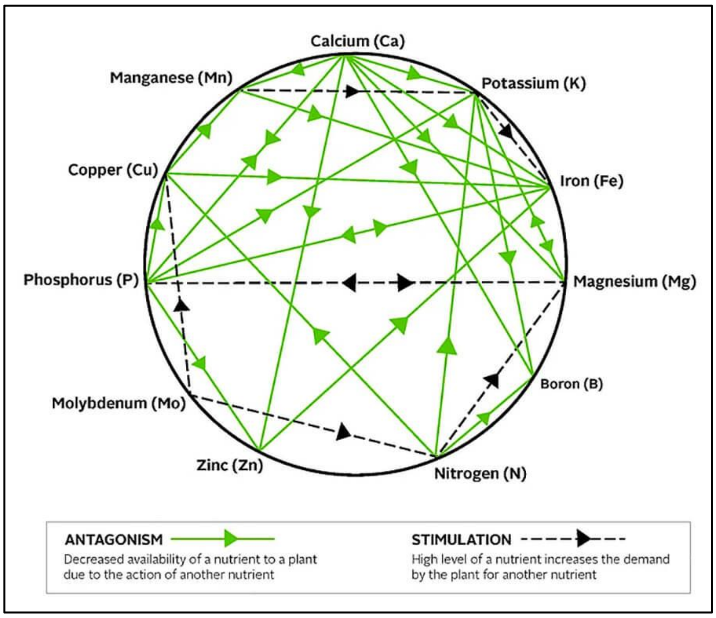


*Figure 15: Mulders Chart: Nutrient Interactions (NutriAg, 2020)*

## 2.2.4 Biological indicators

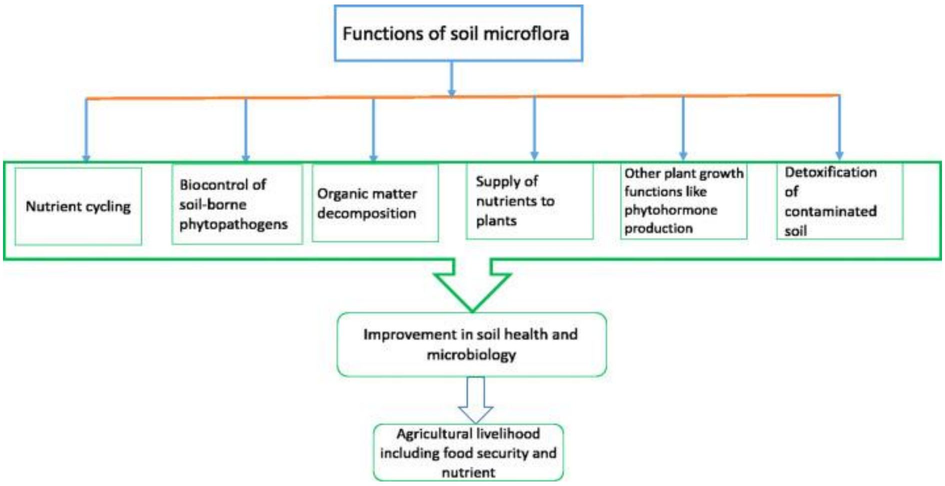


*Figure 16: Functions of Soil microbiology (Tripathi & Devi, 2020)*

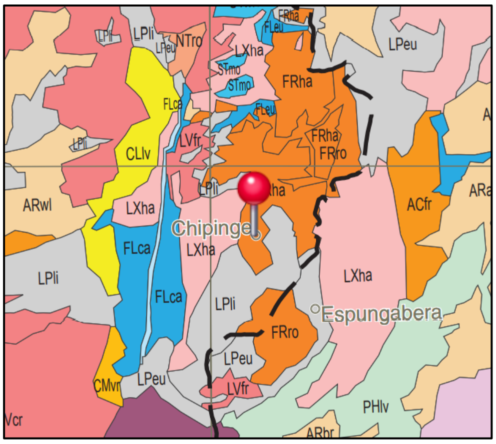
Biological activities play vital roles in nutrient cycling, nutrient availability to plants, developing and maintaining soil structure and enhancing soil health (Smith & Read, 2008). Activity is concentrated in topsoil, up to 30cm deep, microorganisms are drivers in the cycles of N, S, P, and organic residues (Howarth, 2015). Soil microbial communities consist of diverse populations of bacteria, invertebrates, and fungi and are good indicators of soil functionality and soil health, microorganisms control physical properties of soils by exuding polysaccharides and other extra cellular compounds that improve aggregates stability (Smith & Read, 2008). Indirectly microbial activity influences water holding capacity, infiltration rates, crusting erodibility and compaction (Biswas & Naher, 2019). Carbon mineralization is driven by microbes, where organic residues are converted to energy or carbon, however this process can be interfered with by pollutants from inputs, causing CO2 to be respired from the soil, this reduces overall carbon cycling and raises concerns regarding soil health (Fuller, 2005).

Earth worms are indicators of soil health, they are sensitive to changes in their environment, from pH, water logging, compaction, cultivations, and applications of organic matter. They play a vital role in nutrient cycling, incorporating OM into the soil through metabolic processes, their burrows improve drainage and aeration of soil, and create a structure for root development and water infiltration (Smith & Read, 2008).

## 2.2.5 The influence of Soil type on management

The avocado orchards in Chipinge are planted on a soil type called Haplic ferralsols (FRha), these old red soils are associated with high rainfall, with high clay content and high levels of Aluminium and Iron oxides. The strength in this type of soil is it can sustain limited cultivations with the addition of lime and fertilizers, but weaknesses are it requires specific soil management, where natural nutrient levels and nutrient retention is low, this can be addressed with the addition of soil amendments (Jones, et al., 2013). Strong micro-aggregation in the type of soil leads to low water retention capacity, and in dryer times crops can be prone to drought stress. These soils are generally acidic, but can be corrected by liming, however the high Iron content can result in locking up of Phosphorus from fertilizer applications. The biggest threat to this soil comes in the form of erosion and nutrient loss by leaching (Jones, et al., 2013).

Figure 17: Soil map of Chipinge Area (Jones, et al., 2013)



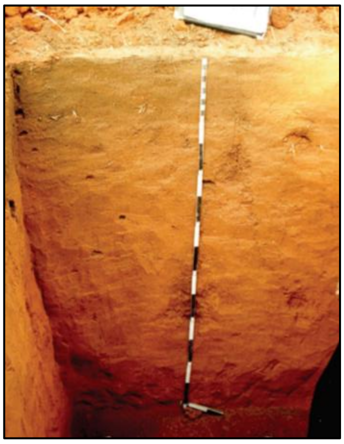


Figure 18:Soil profile of a typical Haplic Ferralsol (Jones, et al., 2013)

## 2.2.6 Soil management in Avocados

Orchards are planted in a systematic pattern and managed to maximise yields, ideally an integrated orchard management practice would comprise of integrated nutrient management, tree canopy and orchard floor management and residue recycling (Das, Kandpal, & Devi, 2021). Integrated nutrient management would include aims of improving overall soil health, by targeting either the rooting area or inter row orchard floor, the addition of organic and green manures, composts, chemical or biological fertilizers, liming, organic amendments, and cover crops (Das, Kandpal, & Devi, 2021). These may vary with the growing season, tree age and soil properties, but whether it’s for soil rehabilitation, maintenance, or improvement, they will reduce negative implications associated with cultivation and improve soil health, drive tree root, and shoot development and increase overall production efficiency.

Figure 19: Inter row cover crop in an avocado orchard (Hammerich, 2020).

Cover crops provide a means to address soil degradation in a universal fashion, they can be grown as an annual crop or perennial culture, a variety of combinations planted in the inter row spaces as shown in figure 19 above, consisting of grasses, legumes, vegetables, or agricultural crops. According to (Ramos, Benitez, & Garcia, 2010) the benefits of cover crops include providing protection against soil erosion by stabilizing topsoil conditions, reducing excessive soil evaporation and minimising effects of prolonged dry periods, they also minimise nutrient leaching from utilization and cycles of leguminous and non-leguminous plants and Nitrogen fixation. Cover crops improve soil quality by increasing microbial activity and biomass, this accumulates SOM and soil aggregate stability with a reduction in bulk density and higher water holding capacity (Das, Kandpal, & Devi, 2021). This a form of conservation agriculture that also provides ecosystem services for the orchard by increasing beneficial insect population and carbon sequestration.

*Figure 20: Avocados with Mulch applied in the rooting zone (Mccarthy & McCauley, 2019).*

Mulches are placed over soil in the rooting zone of the avocado as shown above in figure 20, this simulates the natural environment of the avocado and provides services to the soil in the form of organic materials and decomposes over time to release nutrients and create an environment for ideal root development (Krishnamurthi, 2000). Mulches can be in the form of composted bark/wood chips, green or composted manure or straw mulch, they have differing effects but have similar benefits in that they promote microbial activity that act antagonistically to *P cinnamomi*, over time they improve soil structure, increasing porosity and nutrient availability, they act as a buffer to degrading factors in the form of a protective layer on the surface, limiting water runoff, erosion and reducing soil evaporation rates (Mavuso & Willis, 2007).

## 2.3 Climate

### 2.3.1 Chipinge, Eastern Zimbabwe

The Eastern Highlands area of Zimbabwe is classified into a sub-tropical climatic region, it follows a seasonal cycle with a hot rainy season spanning from November to March and a dry season from April to October, with occasional winter rains in the months of June and July (Wolstenholme, 2013). Annual climate variability influenced by climate change and inter-tropical convergence zones has driven below average rainy seasons known as (El nino) and higher than average rainfall during the dry season known as (La nina) (Weather-and-Climate, 2021).

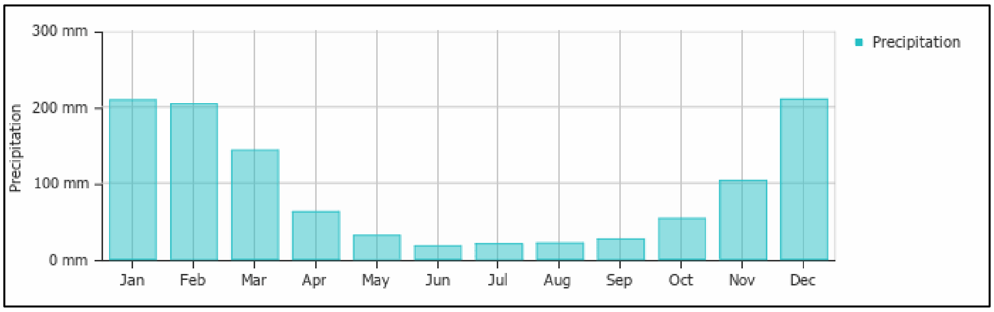


*Figure 21: Average monthly rainfall in Chipinge, Eastern Zimbabwe in millimetres (Weather-and-Climate, 2021)*

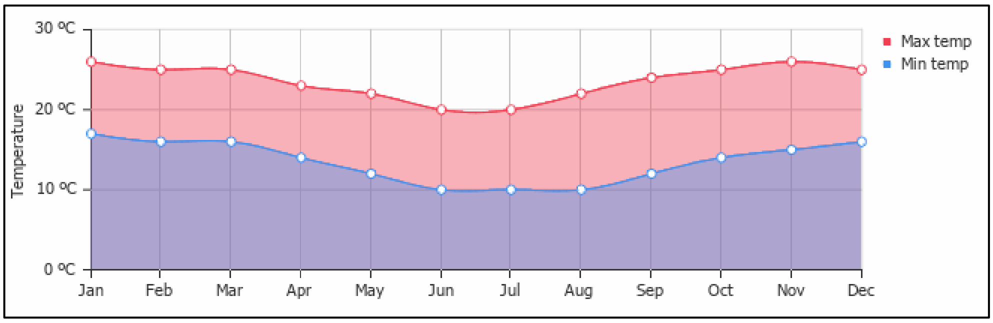


*Figure 22: Average minimum and maximum temperatures in Chipinge (Weather-and-Climate, 2021)*

Temperature in Chipinge has faced an increase of 0.03°C per year since 1970, this has driven a warming trend and intensified droughts towards the end of rainy seasons, as well as colder winters with more frequent instances of frost in winter, a damaging factor for avocados in particular (Wolstenholme, 2013).

# 3. Chapter 2: Methodology

## 3.1 Aim of this Study

The aim of this research is to assess the soil health in different Hass avocado orchards, testing for a broad range of soil health indicators, physical, chemical, and biological. Determining soil status will enable a comparative analysis of the various sites and literature cited and indicate where soil degradation arises due to cultivation practices or lack thereof. This will help to identify a potential solution in the form of a management style to improve soil health status, that can be integrated into the cultivations of the avocado production system.

## 3.2 Research Approach and Data collection

There are 7 similar sized Avocado fields with the same soil type under investigation, the testing will be carried out at 4 farms/estates in the district of Chipinge, 2 fields at Hartbees Nek Enterprise, 4 fields from Rift valley estates (1 at Rusitu and 3 at Croc creek) and 1 field at Enhoek estate. The fields have been categorised into New (1-2 years), Mid (3-9 years), and Old (10+ years). Please refer to the appendix 1 for description of the fields. The sampling will collect quantitative data for the following:

(1) Nutrient status, and pH, SOM, bulk density, and electrical conductivity (EC).

(2) Visual evaluation of soil structure score (VESS score), earthworm count, and Soil moisture content.

Soil test and sample methods for (1) and (2) are taken identically in all 7 fields in a “W” pattern to eliminate potential bias .

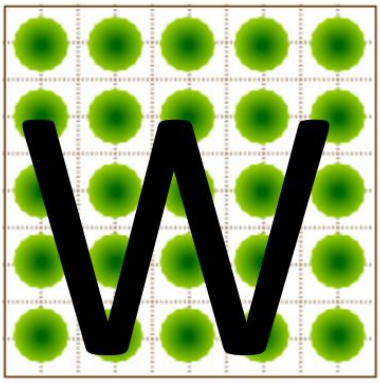


*Figure 23: “W” Sampling method (Popek, 2018).*

### 3.2.1 Sample Method and Analysis for part (1)

Samples for (1) are taken at a depth of 30cm with a spade within the rooting zone that lies between trees along the ridged row of soil, a combined total of 5 samples per field are to be collected to provide enough soil (a total of 2Kg of soil per field) for testing and a reliable source of data for comparison.

The 7 Collected samples were sent to Nutrimaster Harare, laboratory for analytical chemistry services, they are chemically tested, and each specified soil component analysed individually, the testing conditions were specified to be:

1. Trace elements – extracted using 0.05M EDTA pH 7.00
2. Exchangeable Cations – extracted using 1.0M Ammonium Acetate pH 5.8
3. Initial Mineral Nitrogen – Kjeldahl method after extraction with 0.01M KCl
4. Electrical Conductivity – 1 part soil extract with 5 parts distilled water
5. pH – Extraction with 0.01M $CaCl_2$ solution
6. Phosphate – Olsen method
7. Organic Matter – loss on ignition

Macro and micronutrients tested for are: Initial mineral Nitrogen (IMN), Phosphorus pentoxide ($P_2O_5$), K, Ca, Mg, Na, Mn, Cu, Fe and Zn.

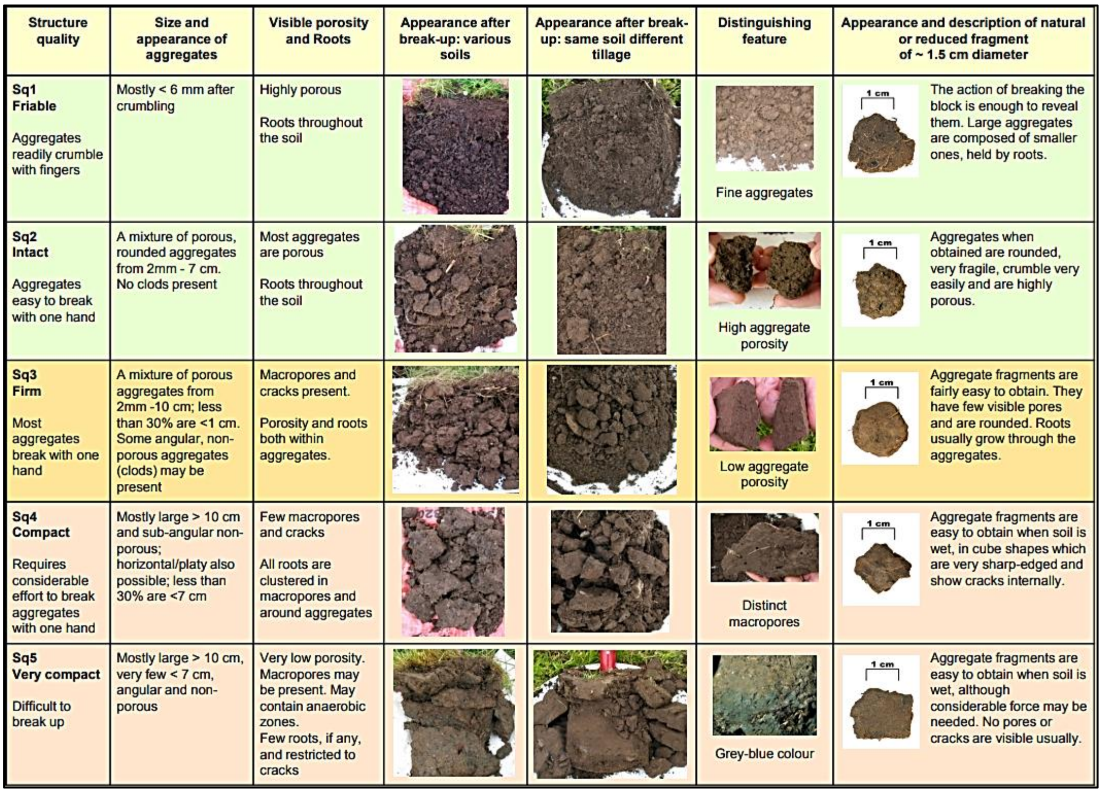
Results are delivered in a table format with interpretable figures, suitable for comparison and evaluation. The data that will be provided for soil nutrient status and structural integrity of the soil, will be in the form of:

1) (µS/cm) for EC
2) (meq/100g) for Ca, Mg, Na, and K
3) (µg/g) for Fe, Mn, Cu, Zn, IMN, and $P_2O_5$
4) ($Kg/m^3$) for bulk density
5) (%) for SOM

### 3.2.2 Sample Method and Analysis for part (2)

Physical evaluations of VESS score and earthworm counts are done personally in the field and moisture samples taken to be assessed under controlled conditions, these tests were all done on the same day to eliminate any external weather and irrigation influences on moisture tests.

A Sample of a VESS score is done carefully by spade within the rooting zone of the tree, dig 3 sides of a square as wide as the spade and 30cm down, the block of soil is then leveraged out with one side undisturbed and placed on an empty bag for evaluation (Askari, Cui, & Holden, 2013). Examination of the block of soil involves breaking up the soil by hand to reveal micro and macro-aggregates, a photograph is then taken to show the physical makeup of the soil. Further assessing of aggregates to reveal size, shape, texture, and visible porosity (Ball, 2019). Figure 24 below is used as a guideline for grading soils, with excellent soil structure graded as Sq1 and very poor soil structure as Sq5.



| Structure quality | Size and appearance of aggregates | Visible porosity and Roots | Appearance after break-up: various soils | Appearance after break-up: same soil different tillage | Distinguishing feature | Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter |
|---|---|---|---|---|---|---|
| **Sq1**<br>**Friable**<br>Aggregates readily crumble with fingers | Mostly < 6 mm after crumbling | Highly porous<br>Roots throughout the soil | | | Fine aggregates | 1 cm<br>The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots. |
| **Sq2**<br>**Intact**<br>Aggregates easy to break with one hand | A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present | Most aggregates are porous<br>Roots throughout the soil | | | High aggregate porosity | 1 cm<br>Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous. |
| **Sq3**<br>**Firm**<br>Most aggregates break with one hand | A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present | Macropores and cracks present.<br>Porosity and roots both within aggregates. | | | Low aggregate porosity | 1 cm<br>Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates. |
| **Sq4**<br>**Compact**<br>Requires considerable effort to break aggregates with one hand | Mostly large > 10 cm and sub-angular non-porous;<br>horizontal/platy also possible; less than 30% are <7 cm | Few macropores and cracks<br>All roots are clustered in macropores and around aggregates | | | Distinct macropores | 1 cm<br>Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally. |
| **Sq5**<br>**Very compact**<br>Difficult to break up | Mostly large > 10 cm, very few < 7 cm, angular and non-porous | Very low porosity. Macropores may be present. May contain anaerobic zones.<br>Few roots, if any, and restricted to cracks | | | Grey-blue colour | 1 cm<br>Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually. |

*Figure 24: Visual Evaluation of Soil Structure (Ball, 2019).*

Earthworm counts were done using the same method of soil extraction used for the VESS score and totalled for each field after 5 samples. Higher earthworm counts will indicate a better soil health.

Soil moisture samples are collected from each VESS score digging site for each field, labelled, and sealed in an airtight bag for moisture testing. A total volume of 200g of soil is required for analysis and samples are processed as follows:

All weights are to 2 decimal places.

1) the wet soil ($S_w$) samples are put into individual dishes and weighed
2) dishes are placed in an oven at 110°C to dry for 24hrs
3) Dry soil weight ($S_d$) is taken immediately after drying to prevent any moisture contraction
4) Soil moisture ($S_m$%) is obtained by formula:

$$Sm = \frac{Sw - Sd}{Sw} \times 100\%$$

Comparison of soil moisture % will indicate moisture retention and water holding capacity for each field (Reeb & Milota, 1999).

# 4. Chapter 3: Results

## 4.1 Results table

| **Sample Fields** | | **Results** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **OM (%)** | **pH** | **Bulk Density (kg/m$^3$)** | **EC (µs/cm)** | **IMN (µg/g)** | **$P_2O_5$ (µg/g)** | **K (meq/100g)** | **Ca (meq/100g)** | **Mg (meq/100g)** | **Na (meq/100g)** | **Soil Moisture (%)** | **VESS Score (sq)** | **Earthworm count** |
| **New** | Field 1 | 9.59 | 5.01 | 1130 | 45 | 10 | <0.01 | 0.17 | 3.24 | 0.96 | 0.06 | 15.22 | 4 | 3 |
| | Field 4 | 4.09 | 5.08 | 1070 | 110 | 20 | 143.84 | 0.54 | 2.61 | 0.56 | 0.04 | 9.76 | 3 | 2 |
| | **NEW AVG** | **6.84** | **5.05** | **1100** | **77.5** | **15** | **71.93** | **0.36** | **2.93** | **0.76** | **0.05** | **12.49** | **4** | **3** |
| **Mid** | Field 2 | 10.2 | 4.92 | 1120 | 43 | 30 | <0.01 | 0.68 | 4.31 | 1.43 | 0.09 | 10.34 | 2 | 2 |
| | Field 5 | 3.41 | 4.00 | 1040 | 341 | 40 | 273.1 | 0.32 | 1.17 | 0.22 | 0.06 | 11.75 | 3 | 1 |
| | **MID AVG** | **6.81** | **4.46** | **1080** | **191.5** | **35** | **136.56** | **0.5** | **2.74** | **0.83** | **0.08** | **11.05** | **3** | **2** |
| **Old** | Field 7 | 10.98 | 5.24 | 820 | 179 | 50 | 1.24 | 0.82 | 4.00 | 1.55 | 0.05 | 21.20 | 1 | 8 |
| | Field 6 | 8.45 | 6.25 | 840 | 318 | 50 | 191.8 | 0.35 | 8.78 | 1.62 | 0.10 | 15.88 | 1 | 7 |
| | Field 3 | 10.27 | 4.78 | 970 | 49 | 140 | 148.6 | 0.68 | 15.58 | 1.78 | 0.12 | 15.32 | 1 | 5 |
| | **OLD AVG** | **9.9** | **5.42** | **880** | **182** | **80** | **113.88** | **0.62** | **9.45** | **1.65** | **0.09** | **17.44** | **1** | **7** |

*Table 5: Results Table*

Please refer to appendix 2 for results table on Mn, Fe, and Zn.

## 4.2 VESS evaluation results

| **Sample fields** | **Visual VESS Comparison** | | |
|---|---|---|---|
| **New** | Field 1<br> | Field 4<br> | |
| **Mid** | Field 2<br> | Field 5<br> | |
| **Old** | Field 7<br> | Field 6<br> | Field 3<br> |

*Table 6: VESS results comparison*

## 4.3 Representation of Results

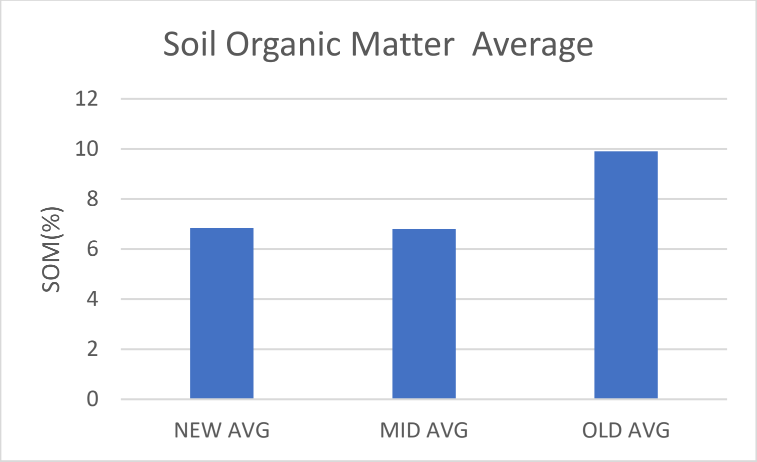


*Figure 25: Soil organic matter Average*

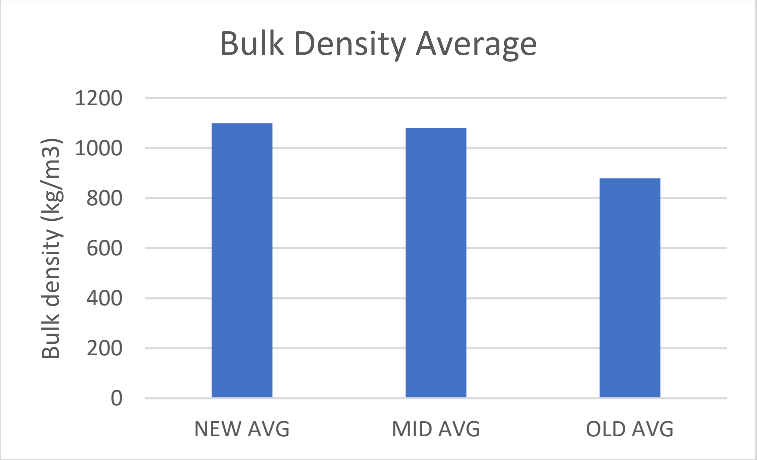


*Figure 26: Bulk density Average*

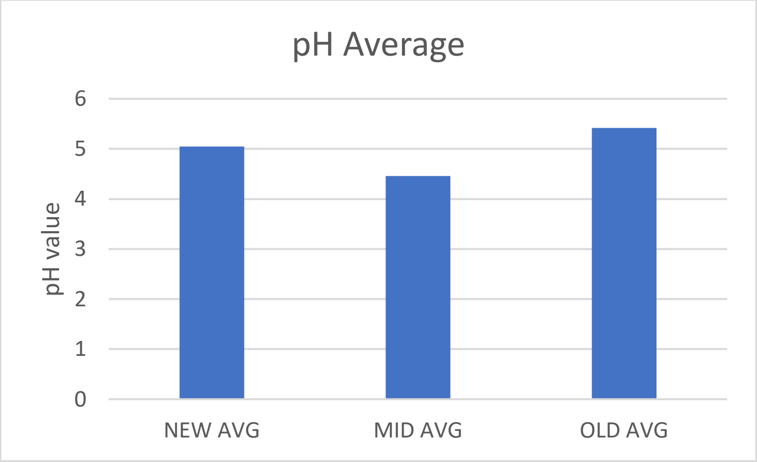


*Figure 27: pH Average*

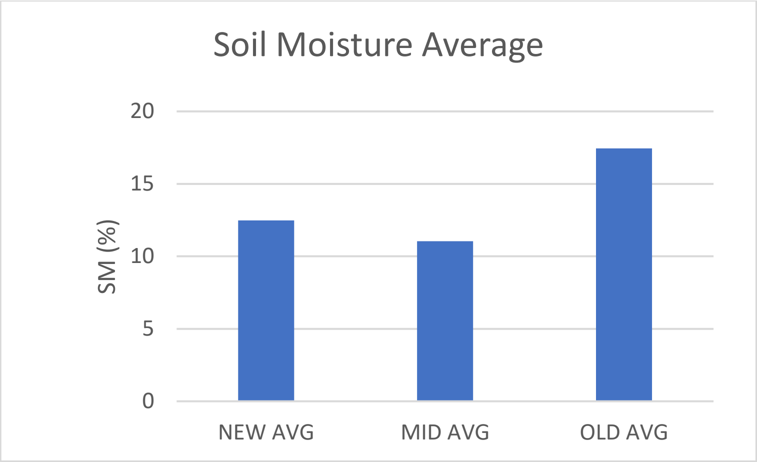


*Figure 28: Soil Moisture Average*

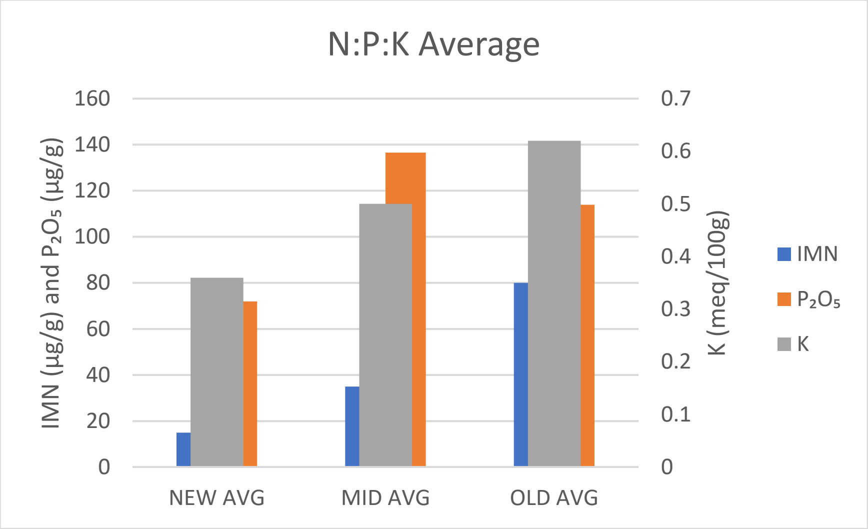


*Figure 29: N, P, and K Averages*

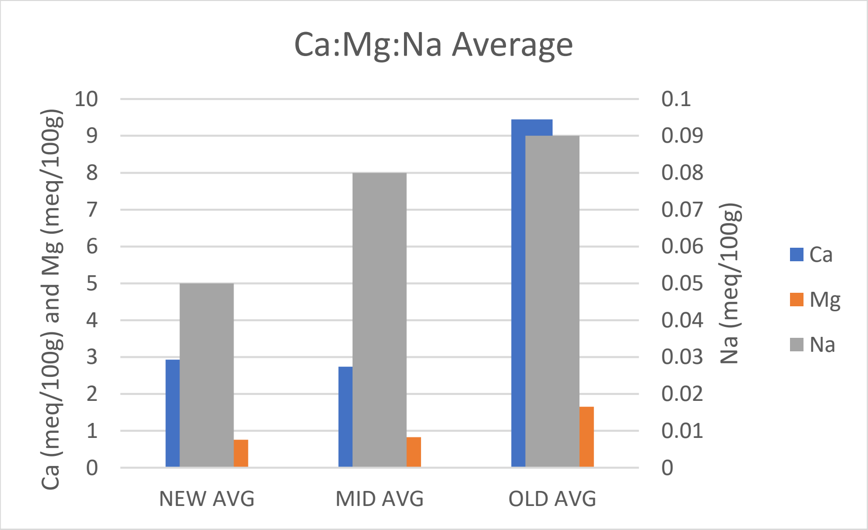


*Figure 30: Ca, Mg, and Na Averages*

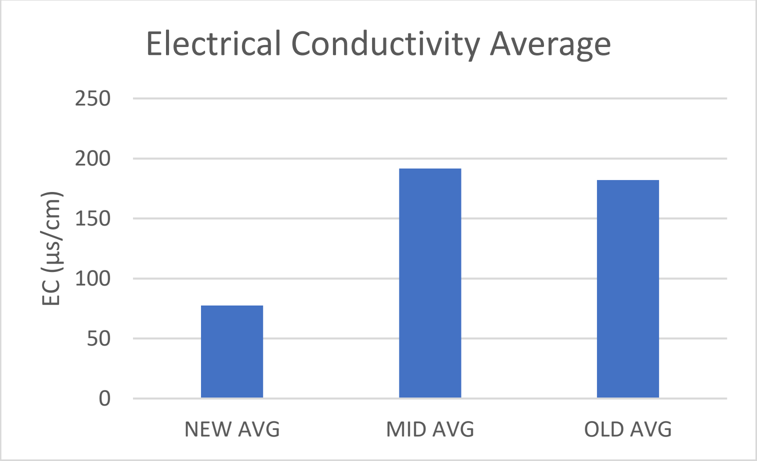


*Figure 31: Electrical Conductivity Average*

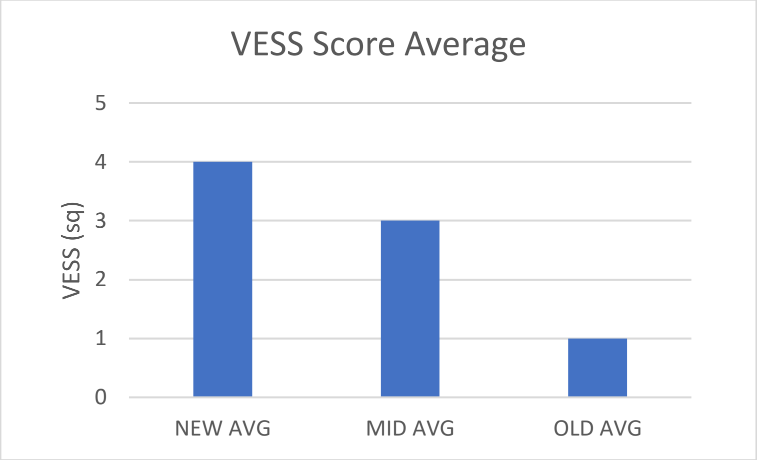


*Figure 32: VESS score Average*

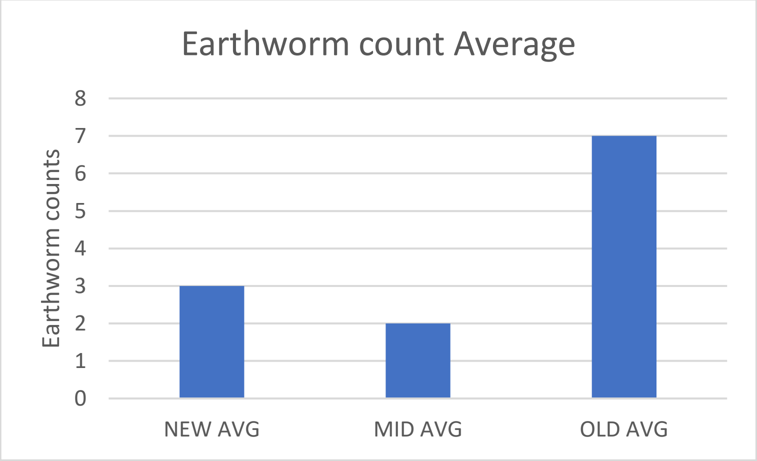


*Figure 33: Earthworm count Average*

# 5. Chapter 4: Analysis and Discussion

## 5.1 Analysis

### 5.1.1 Soil Organic Matter

Degradation of soil health from destructive practices in the avocado orchards would show a pattern of SOM% reduction over time. In figure 25 the old fields show a negative correlation to the theory of loss in SOM% over time. A varied statistic in the new and mid aged fields indicates that a low primary SOM% has either been addressed by adding organic amendments in the form of mulches in the rooting zones, in Field 4 and 5 the SOM status is low from a lack of organic materials and the younger trees are not capable of producing significant leaf litter to cover the soil. The Older trees have a higher canopy density and have a larger area under which foliage can accumulate and breakdown over time, this result correlates to Krishnamurthi's (2000) idea. During initial land preparation, ploughing and subsoiling leads to SOC loss from microbial respiration and decomposition as indicated by (Olson, 2013), this factor may contribute to low initial carbon in the soil. At planting all the fields were sown with a single cover crop, a grass *C gayana*, for erosion control, this has also benefited by adding small amounts organic material annually until they are eventually shaded out by the canopy and die out. The addition of a mono-cover crop has maintained if not improved SOM% from the time of planting but is limited in the sense that it decays slowly.

### 5.1.2 Bulk Density

The comparison in bulk density between the fields in figure 26, indicates that as the orchards get older, the weight per unit volume of soil in the rooting zone decreases, and according to (Bronick & Lal, 2005 ) the lower a soil bulk density is the more it contributes to an overall increase in soil structural quality, a good indication of soil health. According to (Indoria, Sharma, & Reddy, 2020) the high initial bulk density in the new fields, is caused by lack of organic carbon due to increased decomposition and makes the soil more prone to compaction. The distribution of results relates positively to the statement in the literature made by (Imadi & Shah, 2016) that soil subjected to organic matter for a prolonged period, over 5 years will lower soil bulk density, this highlights the importance of organic amendments to soil. A correlation between the pictures of VESS score comparison and results show how macro-aggregates vary in structure, with new and mid fields having less macro-pores per volume of soil compared to the older fields, importantly the higher porosity allows soils more gaseous exchange, higher water infiltration rates and higher water holding capacity, an important factor for nutrient movement and root development. Figure 34 below shows the linear relationship between a deceasing soil bulk density and increasing soil moisture content.

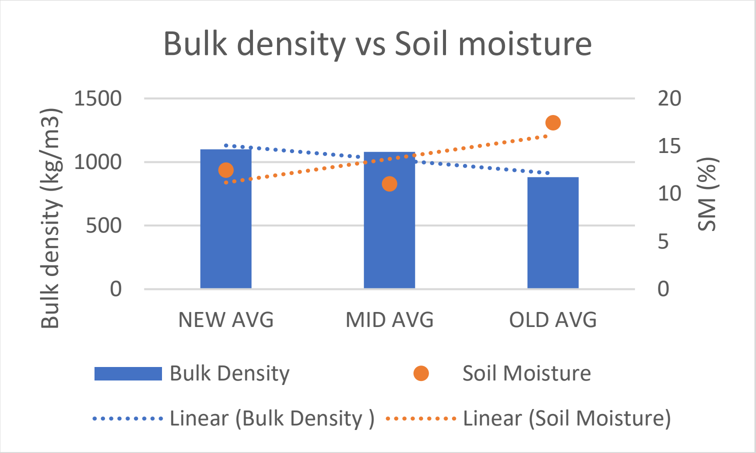


*Figure 34: Bulk density vs Soil moisture*

### 5.1.3 pH

The pH values that represent the fields in figure 27 have shown a variation and some form of decrease from new into mid aged fields, with an increase into the old fields. Naturally these soils are acidic according to (Jones, et al., 2013), the increase in overall pH shows a promising sign that cultivation methods have rather improved than damaged pH levels. Field 6 is subject to a composting experiment and has the highest value of 6.25, closest to the ideal pH of 6.5 quoted by (Wolstenholme & Sheard, 2011), the organic amendments in the compost create a pH buffer, which reduces steep fluctuations in soil acidity, with particular reference to (Jensen & Thomas, 2010) this field will have the most stable soil nutrient status and a higher availability of nutrients for absorption. A decrease in pH values from new to mid fields can possibly be driven by the loss of Nitrogen by leaching, and accumulation of soluble organic and inorganic acids from carbon cycling after a delayed period of limited SOM returns to the soils (Bolan, Curtin, & Adriano, 2005). Improving a soils pH is difficult and takes a long time because initial pH influences active soil microbial biomass that decomposes SOM, limiting organic matter input from slower rates of decomposition and microbial function (Mobilian & Craft, 2021), according to (Ramesh T. , et al., 2019) the favoured method used to raise soil pH involves liming, additionally this will increase plant available elements. Average Ca displayed in figure 30, correlates directly to pH values, this highlights the importance of liming.

### 5.1.4 Soil Moisture

As indicated by (Ramesh T. , et al., 2019) low bulk density and high macro-pore porosity facilitates water movement and water holding capacity. The distribution of SM over the fields in figure 28 is directly related to bulk density scores, the variability in SM is due to the differences in physical attributes of the soil. SM of ≥15% indicate a good soil health and high-water holding capacity, as shown in fields 1, 7, 6, and 3, the graph indicates that SM retention increases as the orchards age, and according to (Ramesh T. , et al., 2019) this is due to an improvement in physical soil conditions over time. Low SM in the new and mid fields can be influenced by (1) lack of canopy and ground cover causing higher rates of soil water loss from evaporation and (2) weak soil structure from land preparation, compaction that reduces infiltration rates and high soil bulk densities that lower water holding capacities.

### 5.1.5 Nutrient Status

Figure 29, represents important nutrients in the avocado growth and development cycle, being N, P, and K concentrations. The results show a general increase in abundance of elements from new to old fields, this distribution correlates to the statement of low nutrient demand by (Lahav, 1995), and indicates that either artificial inputs are not being leached and/or nutrients are being efficiently recycled from organic matter in the topsoil layer and retained. (Jensen & Thomas, 2010) referred to pH as the main limiting factor for availability of nutrients, specifically IMN is subject to this relationship, in the nitrogen cycle low soil pH will reduce N mineralization and lower its availability for uptake, figure 29 shows a significant increase in IMN over the fields and this indicates a high degree of microbial activity that is releasing IMN into the soil. The lower values of available IMN in new and mid fields can be increased at the beginning of an orchards life span by incorporating a mixed cover rather than just grass as a cover crop, the integration of legumes into this will increase N fixation (Dabney, Delgado, & Reeves, 2001).

(Moreira & Martins, 2005) indicated that Phosphorus is an important tool in suppressing *P cinnamomi*, increasing the trees resistance to disease contraction. In figure 29, the new fields showed lower levels of P in the soil, compared to high levels in both mid and old fields, (Smith & Read, 2008) related the increase in P levels to breakdown of organic matter, which is highlighted by the increase in P from new to mid fields. A decrease in P from mid to old fields could be due to demand from fruit development and higher nutrient removal to deposit ratios. The distribution of results indicate that P would need to be increased in new fields when younger trees are most vulnerable to infection from *P* cinnamomi and according to (Lahav, 1995) trees have a low demand for P, meaning variations in mid and old fields are negligible and could be easily corrected and maintained by artificial fertilizers and organic amendments.

Figure 29 shows the distribution of Potassium, with a consist increase from new to old fields, indicating that soils are retaining the element and there is a net positive gain of K over time. The increase in $K^+$ ions play an important role in improving soil health as indicated by (Abercrombie, 2009) by improving pH, EC, and osmotic potential in the soil. K is less available for uptake by plants at low pH and low soil moisture, highlighting the importance of supplementing this element for soil health after demands from fruiting that removes large amounts of this element from the soil.

The distribution of Ca, Mg, and Na in figure 30, show an accumulation of nutrients from new fields to older fields, indicating an improvement in soil health over time. Ca shares an important relationship with soil pH, showing a similar trend over time, when Ca increases so does pH and vice versa as illustrated below in figure 35.

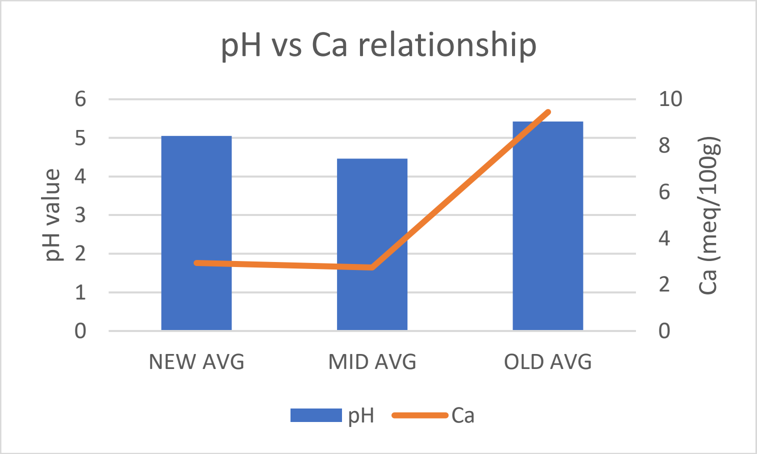


*Figure 35: pH vs Ca relationship*

An increase in available Mg in the fields is beneficial to P uptake according to (Fageria & Gheyi), however if Mg increases and Ca does not, this decreases the Ca:Mg ratios, and weakens aggregate stability (NutriAg, 2020). The distribution of results in figure 30 indicates that these ratios are poor in the new and mid fields at 3:1 compared to 8:1 in the old fields with the ideal ratio for clay soils being 7:1 according to (Symbiosis, 2020), these ratios correlate directly  to VESS score and bulk densities and indicate that they have a great influence on soil health. The ratios in the new and mid fields can be addressed by the addition of Calcitic lime, which has a low concentration of Mg and high Ca.

Sodium concentrations in figure 30, increase gradually from new to old fields, possibly driven by irrigation water, with Na levels lower than 0.7 meq/100g for all the fields, this is a good indication that the soil in general will not be prone to consequences of high exchangeable Na as mentioned by (Laker & Nortje, 2019). Refer to appendix 2 for the increase in nutrients values of Mn, Fe, and Zn.

### 5.1.6 Electrical Conductivity

EC provides an accurate value of various soil properties as indicated by (Husson, Brunet, & Babre, 2018), Figure 31 shows the averages increasing from new to old but a relatively low value of 77.5 µS/cm for the new field compared to mid and old fields. According to (Corwin & Lesch, 2003) the lower reading in the new fields is due to low SOM and low CEC, due to nutrient shortages in the soil, which should be addressed by fertilizing, liming, and organic amendments. The mid and old fields show a similar result, suggesting there is a consistency in soil texture and salinity, an indication of good soil health (Fourie, 2019).

### 5.1.7 VESS Score

VESS is an important visual indicator of physical soil condition, particularly aggregate stability. The results displayed in figure 32, show an average increase in VESS score from new to old fields, which indicates an improvement in soil structural stability over time. (Ball, 2019) described weakly structured soils like the new and mid fields, to have large aggregates with a low porosity, whereas a well-structured soil in the older fields has large aggregates made up of smaller aggregates held by roots and can be broken up easily. Table 6 illustrates field 3 and 6 in the older fields having a darker soil in the upper profile, this is highlighted by (Reeve, et al., 2016) as a high percentage of SOM, with both having scores of 1sq the importance of organic matter to soil structural quality is emphasised. Poor initial soil structure ratings in the new fields, are potentially amplified by cultivations like compaction ploughing (Ditsch, 1986), but are improved intime by the addition of SOC and microbial activity.

### 5.1.8 Earthworm counts

Figure 33 displays biological activity in the fields, with an increase in numbers from new to old fields, (Smith & Read, 2008) quoted that earthworm are very sensitive to environmental changes and related to soil health, the distribution of results shows that numbers are increasing over time which indicates a general improvement in soil health. (Smith & Read, 2008) also indicated that earthworm activity improves soil structure, with higher activity in the old fields this suggests that it will also have a better soil structural quality than the new and mid fields. Addressing low numbers in a new field because of poor soil quality indicators, means that nutrient status and SOM need to be corrected and the numbers will increase with time.

## 5.2 General Discussion

This section will collectively compare the findings of the research and discuss the overall effect of avocado production on the soil.

A report made by both (Ayala, 2020) and (Krosofsky, 2021) stated that intensive Avocado production can lead to various negative impacts on the soil, reducing overall soil health and a loss in soil fertility. It is easy to understand why cultivation can be destructive to soil health, from the action of heavy equipment, the addition of artificial fertilizers and sprays, and large volumes of fruit annually, removing nutrients from the soil as addressed by (Selladurai & Awachare, 2019). The research process analysed some of the key soil health performance indicators, in soils under influence from cultivation in new, mid, and old fields, comparing the state of soil as trees age and production output per hectare increases.

The area under investigation provides the preferred climatic conditions for avocado production as confirmed by (Wolstenholme, 2013). However the soil type being a haplic Ferralsol is naturally poor in nutrients and succumbs to erosion and leaching because of poor soil structures but can be corrected easily as indicated by (Jones, et al., 2013).

The hypothesis states that commercial avocado production in Zimbabwe is damaging to soil health and soil health degrades as orchards age. The analysis showed a contradictive distribution of results to initial thoughts about avocado production in this case, results showed a significant improvement in soil health from new to older fields, showing that there is an accumulation of nutrients over time and a consistent improvement of soil structure within the avocado root zones. The significant difference in soil health characteristics from new to old fields, highlights the integration of physical, chemical, and biological soil health indicators' individual importance in soil health. Some important relationships between key performance indicators were identified, this is a vital part of future management strategies, importantly the correlation between SOM and nutrient availability, soil moisture, and physical soil structure is prominent, highlighting the importance of SOM in a healthy soil.

This experiment showed that an increase in organic matter over time, probably due to accumulation of leaf litter under the canopy, has improved the cyclic relationships of nutrients, soil moisture and physical soil attributes (ARC institute, 2000). A 3% increase in SOM from new to old fields, has reduced the bulk density value by 220 kg/m3 overall, improving water holding and nutrient movement capacities. The higher porosity value of the soil is seen in the figures of soil moisture where it has increased from roughly 12% to almost 18%, the increase in soil moisture content indicates a better holding capacity and infiltration rate, less runoff from compaction will reduce the erosion potential. Nutrient levels have increased considerably, this can be because of an increase in pH levels from 4.5 to 5.5 and organic matter being broken down and recycled, as a result nutrients are more readily available in the soil medium as reflected by higher EC values and accessible to roots. Some nutrient concentrations have shown a fluctuation over the fields, which may cause some form of suppression to other nutrients (NutriAg, 2020), this will more likely influence plant uptake ratios rather than soil health status.

The lower bulk density score has correlated directly with an improvement in VESS score, with values improving from 4sq to 1sq in the older fields, the literature indicates that the higher porosity will have a higher gaseous exchange rate, providing aeration and drainage for the soil, this acts against possible asphyxiation of roots and acts as a suppression tool for *P cinnamomi* (Moreira & Martins, 2005). As stated by (Smith & Read, 2008) soil microbiology is influenced by soil conditions, and the results show an increase in earthworm numbers, relative to VESS score and Bulk density values, providing a more favoured environment.

The fields under investigation have shown a reliable result, indicating that there is no soil degradation as orchards age and therefore it can be said that avocado production improves soil health rather than deteriorate it. The evaluation of the key soil health indicators has shown a promising sign for farmers in the area, their cultivation practices are beneficial, however due to poor initial soil qualities there is room for soil health improvement in the beginning stages of an orchard development to increase the efficiency of the soil resource and ultimately enhance the fertility of the field.

## 5.3 Recommendations for future management

The evaluation of results has shown a consistent improvement in soil health, the factors and some of the relationships from key performance indicators that influence this improvement have been recognized and could provide farmers with crucial information about making future decisions on plantation developments in terms of soil health. Poor soil quality influences performance of trees, especially younger trees and the results indicate that new fields need to be managed more sustainably to improve soil health quicker and reduce the limiting effects of weak soil qualities on growth and development.

A combination of factors can cause an increase in soil quality, (Das, Kandpal, & Devi, 2021) established cover cropping as a soil conservation tool in orchards, to minimise the degree of soil degradation in the early stages of an orchard, however these fields only have a mono-cover crop in and around orchards, a grass *C gayana*, which is beneficial to the soil because it protects the soil surface from erosion and OM in the rooting profile provides structural support to aggregates (Ramos, Benitez, & Garcia, 2010). But the cover crop is limited in the sense that it doesn’t include any legumes, it would be in the interest of farmers to plant a mixed cover crop on the new fields and maintain this cover until it is eventually shaded out, the benefits of a mixed cover to the soil means it would address aggregate stability to a higher degree, and more readily adding organic matter and plant available N to the soil, improving overall soil health as well as more efficient nutrient cycling (Hammerich, 2020).

The relationship between pH and Ca, has been recognized as a key relationship that can be used to adjust soil pH values and availability of macro and micro nutrients, the use of liming methods can greatly influence soil health (Marschner & Rengel, 2012), especially in younger orchards where there is poor soil structure and low available nutrient concentrations, the addition of lime can unlock various nutrients, improve pH and increase microbial activity (Selladurai & Awachare, 2019), this in turn will drive soil microbiology and more efficient nutrient cycling.

The use of organic amendments and plant residue recycling can play an important role in adding carbon to the soil, in these fields most were subject to grass mulch as tool to control moisture loss and capping around basins, this method can be improved by using a compost mixture that contains a variety of decomposed organic materials, these will decay further at different rates and benefit the soil in different ways, (Krishnamurthi, 2000) related the increase in SOM to increased root development near the surface and aeration in soil to be more suppressive against *P cinnamomi* contractions. (Mavuso & Willis, 2007) indicated that soil moisture % is highly influenced by soil structure, organic matter coverage, and canopy area coverage which means it would be in the best interests of farmers to cover as much of the soil surface with organic amendments as economically possible to increase water retention and reduce water loss from the soil surface via evapotranspiration. An important aspect to reduce unnecessary water stress during the important phenological stages of the tree.

# 6. Conclusion

The focus of this study was to prove that commercial avocado production is detrimental to soil health, whether it be influenced by climate change events or damaging avocado cultivation techniques by analysing the key soil health indicators in 3 different aged orchards. The experiment revealed that by nature the region's soil type is poor in structure and has a low inherent pH and nutrient concentration but can be corrected simplistically. The evaluation of results showed that there is a significant improvement in all the soil health indicators, equating to an overall increase in soil quality, disproving the hypothesis. A strong correlation was shown between SOM, tree age and soil health, indicating that SOM is the most influential factor in a soil. The evidence suggested that new fields need to be managed more sustainably at the beginning stages to improve soil structure and this can be done by the addition of various organic amendments and mixed cover cropping.

## 6.1 Limitations of this study

For results to be more reliable the study would need to be carried out in tree rooting zones and along rows where there is traffic movement from spraying, fertilizing, and harvesting this would provide a more generalized result rather than just under the tree canopy. There are some soil health indicators that were not tested for that could provide a more insightful result, microbial biomass which is a good indication of soil condition. Testing for infiltration rates and soil compaction values for accurate hydrologic processes that can be influenced by soil qualities. The study would also prove more reliable if it was tested on more fields of the same age and on different soil types, to give an indication of the rate of improvement for soil health and the degrees to which soil types influence management techniques.

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# Appendices

## Appendix 1: field descriptions

<table>
<tr><td></td><td>Field 1 - Hartbees Nek Enterprise<br>• Age 1 year (2021)<br>• Hass cultivar<br>• West Indian Rootstock<br>• 8m x 4m spacing<br>• Not yet producing<br>• NEW</td></tr>
</table>

*Field 1*

<table>
<tr><td></td><td>Field 2 - Hartbees Nek Enterprise<br>• Age 3 years (2019)<br>• Hass cultivar<br>• West Indian Rootstock<br>• 7m x 3.5m spacing<br>• In production<br>• MID</td></tr>
</table>

*Field 2*

Field 3 – Rift Valley estates, Croc Creek

- Age 15 years (2007)
- Hass Cultivar
- Dusa Rootstock
- 7m x 7m spacing
- In production
- OLD

*Field 3*

Field 4 – Rift Valley Estates, Rusitu Valley

- Age 2 years (2020)
- Hass cultivar
- Dusa Rootstock
- 7m x 3.5m spacing
- Not yet producing
- NEW

*Field 4*

Field 5 – Rift Valley Estates, Croc Creek

- Age 6 years (2016)
- Hass cultivar
- Dusa Rootstock
- 7m x 3.5m spacing
- In production
- MID

*Field 5*

Field 6 – Rift Valley Estates, Croc Creek

- Age 13 years (2009)
- Hass cultivar
- Dusa Rootstock
- 7m x 7m spacing
- In production
- OLD

*Field 6*

Field 7 – Enhoek Estates

- Age 9 years (2013)
- Hass cultivar
- Duke 7 Rootstock
- 7m x 7m spacing
- In Production
- OLD

*Field 7*

# Appendix 2: Mn, Fe, and Zn results

| **Sample Fields** | | **Results** | | |
|---|---|---|---|---|
| | | **Mn (µg/g)** | **Fe (µg/g)** | **Zn (µg/g)** |
| **New** | Field 1 | 184.63 | 60.2 | 0.92 |
| | Field 4 | 55.43 | 73.86 | 4.83 |
| | **NEW AVG** | **120.03** | **67.03** | **2.88** |
| **Mid** | Field 2 | 469.35 | 161.01 | 1.3 |
| | Field 5 | 51.95 | 78.85 | 6.55 |
| | **MID AVG** | **260.65** | **119.93** | **3.93** |
| **Old** | Field 7 | 54.45 | 68.97 | 14.49 |
| | Field 6 | 119.46 | 327.2 | 15.99 |
| | Field 3 | 815.76 | 155.29 | 44.34 |
| | **OLD AVG** | **329.89** | **183.82** | **24.94** |

*Table 7: Results table*