# YIELD AND QUALITY DECLINE IN VEGETATIVELY PROPAGATED CULTIVAR TEA (C*AMELLIA SINENSIS* (L) O. KUNTZE) UNDER CONTINUOUS MECHANICAL HARVESTING

**by**

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# DECLARATION

I, Godwil Mirirai Madamombe, declare that the thesis which I hereby submit for the degree *Philosophiae Doctor* (Horticultural Science) at the University of Pretoria is my own work and has not been previously submitted by me for a degree at this or any other tertiary institute.

Signed……………………………………………………………….

Date…………………………………………………………………..

## DEDICATION

This thesis is dedicated to my wife Esther and my three children: Kudzai Berry, Kundai and Kudakwashe Madamombe whose moral support and inspiration provided the motivation to pursue this PhD studies and particularly to undertake this thesis project. I also dedicate this thesis to my mother Elinah Madamombe, you have always been an inspiration in my life and your words of encouragement have spurned me on.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| **SABINA** | Southern African Biochemistry and Informatics for Natural Products |
| **POL-SABINA** | The Policy and Support Actions for Southern African Natural Product Partnership |
| **TRFCA** | Tea Research Foundation of Central Africa |
| **TBCA** | Tea Brokers of Central Africa |
| **HP** | Hand plucking |
| **HHM** | Hand-held machine |
| **ROM** | Ride-on machine |
| **1 + b** | One leave and a bud shoot |
| **2 + b** | Two leaves and a bud shoot |
| **3 + b** | Three leaves and a bud shoot |
| **4 + b** | Four leaves and a bud shoot |
| **kg mt $ha^{-1}$** | kilograms made tea per hectare |
| **kg GL $ha^{-1}$** | kilograms green leaf per hectare |
| **kg N $ha^{-1}$ $yr^{-1}$** | kilograms nitrogen per hectare per year |
| **MJ $d^{-1}$** | Mega joules per day |
| **W $m^{-2}$** | Watts per square meter |
| **mg $kg^{-1}$** | milli grams per kilogram |
| **m.a.s.l.** | Meters above sea level |
| **PAR** | Photosynthetically active radiation |
| **FI-PAR** | Fractional interception of photosynthetically active radiation |
| $A_{max}$ | Photosynthetic rate |
| **LSD** | Least significant different |
| **SED** | Standard error of the difference of means |
| **CV** | Coefficient of variation |

**Yield and quality decline in vegetatively propagated cultivar tea (C*amellia sinensis* (L) O. Kuntze) under continuous mechanical harvesting**

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**ABSTRACT**

Manual plucking is highly labour intensive, occupying almost 70% of the total labour force on tea estates and accounting for approximately 40 - 45% of cost of production. The high labour costs and shortages and the cost of production has resulted in tea (*Camellia sinensis* (L) O. Kuntze) industries in central and southern Africa becoming unprofitable. The solution to this problem has been the full mechanization of shoot harvesting, however, a reduction in yield and quality has been observed with mechanical harvesting. The overall aim of the study was to determine the causes of yield and quality decline in mechanically harvested tea and if higher nitrogen application rates could mitigate against the yield and quality decline. In order to achieve these aims, field experiments were carried out at Tingamira Estate, Chipinge, Zimbabwe and consisted of seven treatments laid out in a 2 x 3 factorial plus added control experiment, in a randomized complete block design replicated three times. Three harvesting methods (hand plucking performed every 10/11 days, hand-held and ride-on machines performed every 14 days) were tested against three fertilizer application rates (265, 300 and 400 kg N $ha^{-1}$ $yr^{-1}$), with hand plucking (265 kg N $ha^{-1}$ $yr^{-1}$) being the standard.

The study showed that highest yields were produced under hand plucking (HP) across all seasons (43 945 kg green leaf $ha^{-1}$ $yr^{-1}$) as compared to hand-held (HHM; 35 114 kg green leaf $ha^{-1}$ $yr^{-1}$) and ride-on machines (ROM; 36 268 kg green leaf $ha^{-1}$ $yr^{-1}$ ($p < 0.05$).

Continuous mechanical harvesting therefore reduced yield, with yield declining between 17% and 19% compared to hand plucking over the three year pruning cycle. This reduction in yield was associated with a decrease in both the number and mass of desirable shoots in each season. This was largely due to the indiscriminate removal of foliage by the machines, which resulted in the proliferation of immature shoots, with an associated increase in sink strength and competition for available photo-assimilates. In addition, the maintenance layer was depleted in mechanically harvested bushes. This was indicated by reduced fractional interception of photosynthetically active radiation in the top 10 cm in these bushes and reduced photosynthetic rates in these bushes. This suggests that these bushes were also source limited, as compared to hand plucked bushes. Therefore the changes in tea bush architecture, as a result of mechanical harvesting, resulted in changes in sink/source dynamics, which led to a proliferation of immature shoots which competed for limited photo-assimilates.

The decline in yield in mechanically harvested tea has also been associated with a decline in tea quality. In this study hand plucking resulted in a higher % of good leaf quality compared to machine harvesting treatments in the first two seasons, irrespective of N application rate. However, in the third season there were no differences in % good leaf between treatments. Tea tasters' assessments in the third season also showed that there were no significant differences in liquor colour and strength, briskness, brightness and total tea tasters' valuation between hand plucking and mechanical harvesting. However, seasonal differences were observed with higher scores and valuation being observed in the off - season (May 2013), as compared to the main growing period (February 2013). High N-rates tended to reduce made tea density and % fibre content under machine harvesting, but there were no significant differences between treatments. Based on organoleptic evaluation scores and taking hand plucking as a standard for good quality, the harvesting techniques did not show any differences in quality. An analysis of biochemical compounds, important for black tea quality, in tea from February 2013 and May 2013 showed no difference between harvesting techniques and N-application rates. However the dimers and trimers of smaller catechins produced during harvesting initiating field fermentation increased in mechanically harvested bushes and with higher N-application rates, as compared to hand plucking. This could possibly have improved quality in mechanically harvested teas. Based on these results mechanical harvesting can be used as an alternative to hand plucking, as it does not adversely affect black tea quality as previous believed.

To mitigate against the observed yield decline in mechanically harvested tea bushes, higher N-application rates were proposed. Increasing N application rate from 265 to 400 kg $ha^{-1}$ $yr^{-1}$ improved tea yield significantly ($p<0.05$) by 4-10% under the ROM and HHM compared with hand plucking. Yields increased by 19% when N rate was increased from 265 to 400 kg N $ha^{-1}$ $yr^{-1}$ and by 17% from 300 to 400 kg N $ha^{-1}$ $yr^{-1}$ , over the three year pruning cycle. Increasing N fertilizer rates, however, did not improve % green leaf quality significantly. It was only in the third season that % good leaf equalled that of hand plucking, however, this effect was attributed to an effect of the machine harvesting rather than the additional application of nitrogen. It was also apparent that increasing N-application rates to 400 kg N $ha^{-1}$ $yr^{-1}$ did not lead to significant nitrate leaching below the active root zone. This study further showed that in two of the three seasons HHM and ROM at 400 kg N $ha^{-1}$ $yr^{-1}$ resulted in the highest income and return per dollar invested. Therefore, increasing N fertiliser rates to 400 kg $ha^{-1}$ $yr^{-1}$ under machine harvesting technology can play a significant role in reducing the negative impact of machine harvesting on tea yield, with no impact on tea quality. The increased N application rates also have negligible environmental impacts through nitrate leaching and environmental contamination. However, the increased potential for nitrate leaching in areas with higher rainfall could be combated by increasing the number of split applications.

# CHAPTER 1
## General introduction

Harvesting is an expensive operation in tea production, accounting for approximately 40 to 45% of the field management costs (Burgess*, et al.*, 2006) and about 70% of the total labour force deployed on a tea estate (Goldsmith and Kilgour, 1999). Tea industries in central and southern Africa (Malawi, Mozambique, South Africa, Zambia and Zimbabwe) have in the past largely relied on manual labour for harvesting of tea. However, shortage of manual pluckers and/or the cost of the labour (de Jong, 1998) has affected tea cultivation in the region from the early 1990s. The extent of the labour problem has varied between countries and among estates within the tea producing areas. For instance, farmers along the eastern border of Zimbabwe have been severely affected by labour shortages due to the low minimum wage and industrial unrest (Masasa, 1999). The increasing difficulty of acquiring the necessary number of pluckers, and problems related to their management and control, is affecting the viability of the tea industry in this region (Stone, 1999). The increasingly shrill demand for adherence to Western norms, such as Fair Trade practices (Rain Forest Alliance, Ethical Tea Partnership and GlobalGap), has resulted in an increase in expenditure on housing, water supply and social amenities (Cameron, 1999). This initial capital outlay is having an impact on the cost of labour. For example, South Africa is largely reliant on imported labour, which is not only expensive, but also requires large infrastructure for housing.

In Zimbabwe the labour shortage has been aggravated by the return of what had been a 'captive', highly experienced plucking force to Mozambique in 1991/1992, following the political stability in that country and the effort to recruit Zimbabweans was unsuccessful. By 1994 as much as 25% of the crop was being lost, as it was no longer possible to keep to plucking rounds (Stone, 1999). This increased to between 30 and 40% by 2005/2006. The labour problem was so serious in Zimbabwe that some estates, for example Eastern Highlands Plantation Limited, Roscommon and Southdown estates, could not always keep up with their rounds and had to abandon plucking on some of the fields, which caused the tea bushes to over-grow, a condition commonly known as "mothballing". To overcome such problems, Southdown Holdings adopted extensive mechanical harvesting, where 70% of the total tea area (1 200 ha) was under mechanical harvesting (Martin, 2000).

Kawalazi tea estate in northern Malawi has experienced a similar problem and relies on migrant labour from southern Malawi. This labour force is associated with significant transport expenses and inconveniences of bringing labour from the southern districts, approximately 1000 km away from the estate (Martin, 2000). The estate is also forced to pay the workers throughout the season and provide accommodation and other social amenities in order to retain the labour, even during the off-season. The estates also face competition from other enterprises, such as tobacco, which is more profitable. Recently, Malawian tea labour has migrated to tobacco farms, as far away as Tanzania. Not only is the labour shortage due to competition from other crops, but in some areas, there is also a shortage of men and women willing to undertake this repetitive work on a continuing and reliable basis (Burgess*, et al.*, 2006).

This has been the case in Zimbabwe where manual labour is not only very expensive, but also not readily available because the available labour opts to engage in other income generating activities, such as gold/diamond panning (Chimanimani district, Manicaland province) and cross border trading in various commodities. This is aggravated by the fact that most tea estates in Zimbabwe are located in Manicaland province, which is endowed with rich mineral resources and also along the border with Mozambique, making it easy for cross border trade (Figure 1.1) in various commodities. Besides gold panning and cross border trading which, are prevalent in the Eastern districts of Zimbabwe, according to Burgess*, et al.* (2006) and Salvatian*, et al.* (2014), the critical times of peak tea production, for example, after the start of the rains, coincides with other labour intensive activities, such as the weeding of maize and rice cultivation. The HIV/AIDS pandemic and the reluctance to work in tea fields by the younger generation are cross-cutting problems in many tea growing areas and across the farming areas and enterprises in the southern African region, calling for new strategies to plan for this declining workforce (Burgess*, et al.*, 2006)

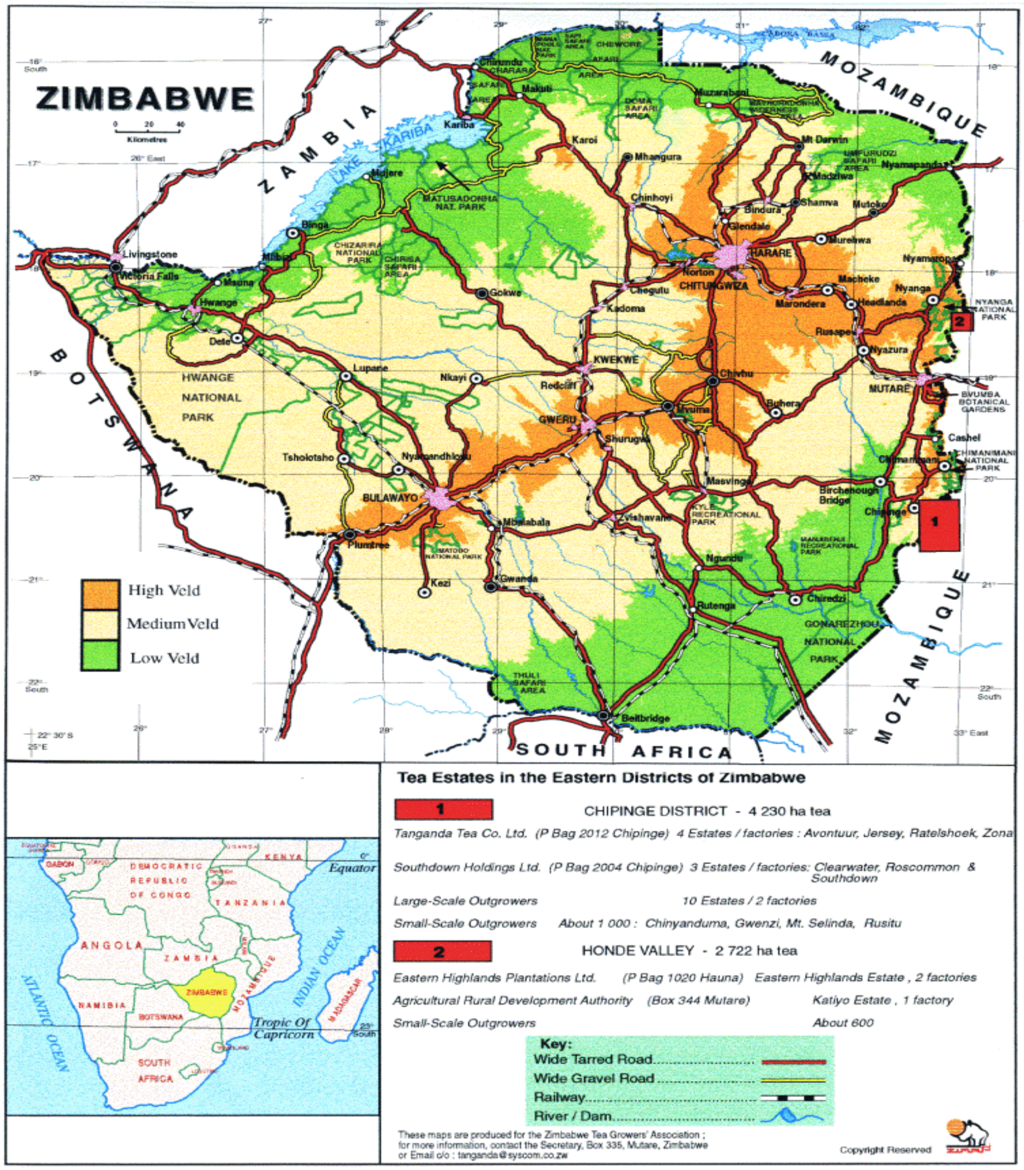


**Figure 1. 1 Zimbabwe tea growing regions (Adopted from the Zimbabwe Tea Growers, 2003)**

It was against this background of high labour costs and unavailability that producers in central and southern Africa had to actively seek alternative, but appropriate, ways for improving the productivity of tea harvesting. The choice is wide, from simple mechanical hand-held aids like shears, motorized cutter bars (which may be hand-held, pushed on wheels, or self-propelled), to large-scale machines harvesting two or three rows of tea at a time (Burgess*, et al.*, 2006).

The move was, however, not a smooth one. Semi-mechanical equipment, such as shears, were introduced around 1992/1993 as the next step from hand plucking and as the first move towards full mechanization. However productivity was not improved as anticipated (Nyasulu, 2001), as bushes were damaged and quality was reduced. The failure to increase labour productivity and/or to reduce number of pluckers meant that other alternative methods had to be found. As a result the full mechanization of tea harvesting was introduced in Zimbabwe around 1999 (Stone, 1999). Whereas, according to Steenkamp (1999), South Africa took this route much earlier than all other estates in central and southern Africa, after having experienced these labour problems, for example Senteeko estate introduced mechanical harvesting as early as 1977/1978. However, information was lacking on the agronomic performance of tea cultivars for machine harvesting, yield and quality of machine harvested tea and best management practices for producing tea intended for machine harvest. According to Burgess*, et al.* (2006), selection of the appropriate system depends on social, financial, technical, and environmental factors, such as the availability and skill of the labour, the capital investment and running costs, the supporting infrastructure for machine maintenance, and the terrain. This meant that research had to be performed to generate information on how best to handle/manage the tea bush to optimize yield and quality and how to make the method more attractive and viable to the tea industry.

Research on mechanical tea harvesting in Malawi and Zimbabwe (Nyasulu, 2006) (Madamombe, 2008) and Kenya (Bore, 1997) examined a number of parameters (plucking round length, shoot density before and after plucking, shoot wet and dry mass, green leaf composition, plucking origin, shoot growth and yield) and how these were affected by mechanical harvesting. The greatest composition of immature shoots, buds, one and bud, two and bud, over grown shoots (>3+b), hard banjhi and broken pieces of stem and leaf and a consistent trend of a reduction in yield and quality was observed with mechanical harvesting. A hard banjhi is a small, dormant apical bud with one, two or three fully expanded hard leaves (TRIT, 2002).This was attributed to the non-selective nature of the harvesting machine when plucking shoots, resulting in shoots of different sizes being plucked, with a mixture of shorter and longer shoots due to the overlapping shoot generations (Nyirenda, 2001), which impacted quality. This is in comparison with hand plucking, where shoots consisting of two leaves and a bud and three leaves and a bud are selectively plucked.

Tanton (1979), reported that in Malawi, for tea under hand plucking, 42-days old shoots are selectively harvested every 7 to 14 days. However, under mechanical harvesting the ability to select for only mature 42-day shoots is difficult due to overlapping shoot generations at the plucking table (Nyirenda, 2001), hence a mixture of shoots are harvested, which includes immature, mature and overgrown shoots (Madamombe, *et al.*, 2015). The majority of shoots are, however, harvested before they reach their optimum size, which has a detrimental impact on yield (Tanton, 1979).

Mechanical harvesting reduces the leaf area index (LAI) of the tea bushes, as a result of the continuous removal or reduction of maintenance foliage. This negatively impacts the photosynthetic activity of the tea bush (Jayasinghe, *et al.*, 2014, Kumar, *et al.*, 2015) and potentially reduces the overall productivity of the plant, as these are the most productive leaves in terms of photo-assimilate supply. This phenomenon is expected to be more pronounced in teas which have small and erect leaves, such as China tea, or clones with broad and erect or semi erect leaf pose, e.g. PC 81, whereby the machine can cut more than half of the leaf during plucking (Burgess, *et al.*, 2006). Sink/source relations are therefore likely to be more negatively impacted in machine harvested tea bushes as compared to hand plucked bushes.

This study therefore aimed to determine if machine plucking, because of its lack of selectivity, removes shoots and/or maintenance foliage which disturbs photo-assimilate production and the accumulation of carbohydrate reserves for regrowth in the long term. It also aimed to assess possible mitigating actions to avoid the decline in yield under mechanical harvesting. In commercial production of tea there is continuous removal of nutrients from the soil, as a result of continual plucking of the young tea shoots and these nutrients are not always adequately re-supplied (Li, 2004). According to Li (2004), the application of fertilizers is therefore recommended annually for sustained yields and high quality, because nitrogen is markedly and positively correlated with amino acid concentration, an important determinant of tea quality. Ordinarily, the schedule of fertilizer application is determined according to the nutritional status of the soil, the yield level in the previous pruning cycle and the yield predicted by agro-meteorological conditions (Li, 2004). The norm in Zimbabwe is to apply fertilizer based on field productivity, such that high yielding fields will get high rates of fertilizer, with low yielding fields receiving less (TPH, 1990). Norms for fertilizer application were also designed for hand plucked bushes and these recommendations have remained unchanged, despite the bushes being predominantly mechanically harvested. The absence of research on the effect of continuous mechanical harvesting of tea on the nutrient budget, especially nitrogen, hampers the development of ecologically sound and economically profitable nitrogen management strategies (Kamau*, et al.*, 2008). It is postulated that the total amount of nitrogen removed from the tea bush during continuous mechanical harvesting may be important in determining the yield and quality of tea and the photosynthetic rates in the tea bush and therefore carbohydrate accumulation for recovery growth following plucking.

### 1.1 Problem statement

Tea harvesting is labour intensive and periodic threats to labour availability and costs, and the general reluctance to work on farms, have prompted the tea industries to mechanize tea harvesting. However, a decline in yield and quality was soon observed under mechanical harvesting. The reason for the yield decline under continuous mechanical harvesting has long posed a great challenge to the tea industry in central and southern Africa. Wijeratne (1999), has attributed the yield decline to a higher percentage of immature shoots harvested by mechanical plucking. As well as influencing the yield and quality characteristics of the harvested crop, the method of shoot removal can affect the number, size and type of shoots remaining on the bush (Burgess*, et al.*, 2006). The indiscriminate removal of the young shoots from the plucking table, which are the strongest sinks (Manivel and Hussain, 1982a, De Costa*, et al.*, 2007), alters the interception dynamics of photosynthetically active radiation (PAR) and sink/source relationships within the canopy. As a result plant photosynthesis within the bush canopy is impacted, which ultimately impacts tea bush productivity and quality.

It is not only important to examine the causes of yield decline and quality in mechanically harvested tea, it is also important to study how best to prevent this from happening. The information gained in this study will therefore be used to minimize the negative effects of machine harvesting on yield and quality of tea. If productivity can be improved, this technology will be far more attractive, resulting in wide spread adoption. Other benefits would include higher labour productivity and less cost per kg of plucked leaf, leading to higher income per hectare, thereby making tea cultivation a viable business. Management will also have greater flexibility, allowing more time to be spent on other activities. In addition, lower labour requirements will reduce costs for infrastructure development and social welfare.

### 1.2 Hypotheses

The effect of continuous mechanical harvesting of tea on yield and quality decline is best understood in the context of its relation to parameters of tea growth and development. It is of great importance to determine how mechanical tea harvesting affects shoot generations per unit area and the growth and shoot population of the bush that reaches physiological maturity. The main hypotheses to be tested in this study were therefore linked to the reasons for the decline in yield and quality of continuous mechanically harvested tea bushes and possible mitigating actions to prevent or at least minimize these declines. The hypotheses were as follows:

1) The decline in yield as a result of mechanical harvesting is a result of the indiscriminate removal of shoots during mechanical harvesting leading to a change in the PAR and sink/source relationships. As a result leaf photosynthesis within the canopy was altered, which ultimately impacts tea bush productivity.
2) Mechanical harvesting of tea can be used as an alternative to hand plucking as it does not reduces black tea quality in terms of tea tasters' valuation, made tea density, fibre content and biochemical compounds.
3) Increasing the nitrogen application rate under continuous mechanically harvested tea from the 265 kg N $ha^{-1}$ $yr^{-1}$ norm to increase yield will not lead to a reduction in

the quality of good leaf and black tea in terms of tea tasters' valuation, made tea density and fibre content and biochemical parameters.

4) The costs of additional fertilizer applied over and above the 265 kg N ha$^{-1}$ yr$^{-1}$ increases with an increase in N-application rate, leading to a reduction in income and the return per dollar invested.
5) The decline in tea yield under mechanical harvesting could be mitigated by increasing the N-application rate from the 265 kg N ha$^{-1}$ yr$^{-1}$ norm with little environmental impact from nitrate leaching

### 1.3 Main objective

The overall aim of the study was to determine the causes of yield and quality decline in mechanically harvested tea and if higher nitrogen application rates could mitigate against the yield and quality decline.

### 1.4 Objectives

1) To determine how continuous mechanical harvesting influences sink/source relationships and the interception of PAR by the tea bush and how this relates to a decline in tea yield.
2) To determine whether continuous mechanical harvesting of tea can be used as an alternative to hand plucking as it does not reduces black tea quality in terms of tea tasters' valuation, made tea density, fibre content and biochemical compounds.
3) To determine the effect of continuous mechanical harvesting and increasing N-application rate on quality of good leaf and black tea quality in terms of tea taster's evaluation, tea density, fibre content and biochemical parameters.
4) To determine whether the cost of the additional N applied due to an increase in N-application rate from 265 - 400 kg N ha$^{-1}$ yr$^{-1}$ will lead to a reduction in income and the return per dollar.
5) To determine the effect of increasing N-application rates above the 265 kg N ha$^{-1}$ yr$^{-1}$ norm on nitrate leaching so as to determine the optimal N- application rates for continuous mechanical harvesting techniques
6) To determine the impact of increasing nitrogen fertilizer application rates on tea yield and green leaf quality under continuous mechanical harvesting.

**1.5 Thesis outline**

The approaches used to test the hypotheses and address the objectives are presented in separate chapters, with the chapters presented in article format as follows:

Chapter 2 is the literature review, which provides a general background to the study, with discussion on the origins of tea and global tea production, ecotypes of tea, determinants of yield and quality of tea (biomass production, environmental factors and agronomic practices impacting tea yield and quality), tea harvesting methods and tea production in Zimbabwe and mechanical harvesting in Zimbabwe and Malawi.

Chapter 3 is a General Materials and Methods chapter and presents information on field site description, rainfall and temperature, experimental design, yield and yield components. This is to avoid unnecessary repetition throughout the thesis.

Chapter 4 unravels the radiation interception dynamics within the tea bush canopy and the source/sink relationships, as affected by the different methods of harvesting. It also tackles the photosynthesis of the tea bush at different canopy layers (This chapter was published in ***Scientia Horticulturae,194, (2015) 286-294)***.

Chapter 5 examines how continuous mechanical harvesting of tea and nitrogen fertilization impacts black tea quality. The different harvesting methods were investigated in terms of their impact on tea density, tasters' valuation, fibre content and biochemical parameters. The effect of increasing nitrogen application rates on these black tea quality parameters was also explored.

Chapter 6 explores how increasing nitrogen application rates can mitigate the yield and quality decline under continuous mechanical harvesting. The ability of increased application rates of nitrogen fertilizer to increase yield and quality of continuous mechanically harvested bushes to a level comparable with hand plucking is assessed. As a result the optimum application rate of N-fertilizer for continuous mechanically harvested tea is suggested which gives both good yield and quality leaf.

Chapter 7 provides a general discussion of all the results from this study and provides recommendations for further studies.

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# CHAPTER 2

## Literature review

### 2.1 Origins of tea and global tea production

Tea (*Camellia sinensis* (L.) O. Kuntze) is an evergreen woody perennial tree, with its origins in the forests of Assam in India and China. China is credited with introducing tea to the world, though the evergreen tea plant is in fact native to southern China, north India, Myanmar and Cambodia (Hicks, 2009). The Chinese dominated the art of tea cultivation for many centuries (Bandara, 2012). According to Bandara (2012), tea was introduced to Japan from China in the early part of the 18$^{th}$ century, which then spread to Indonesia, India and Sri Lanka in the late 18$^{th}$, 19$^{th}$ and late 19$^{th}$ centuries. Tea cultivation in Russia started at the end of the 19$^{th}$ century and in east African countries during the early 20$^{th}$ century (Bandara, 2012). It is widely cultivated around the world with approximately 2.72 million ha of land under tea cultivation globally (Iori*, et al.*, 2014). World tea production (Black, Green and Instant) increased significantly by 6% to 5.07 million tonnes in 2013 (Chang, 2015). Growth in world output was due to major increases in the major tea producing countries. According to Chang (2015), China remains the largest tea producing country with an output of 1.9 million tonnes, accounting for more than 38% of the world total, followed by India (1.2 million tonnes), Kenya (436 300 tonnes), Sri Lanka (343 100 tonnes), Indonesia (152 700 tonnes), Bangladesh (66 200 tonnes), Uganda (58 300 tonnes), Malawi (46 500 tonnes), Tanzania (32 400 tonnes) and Rwanda (25 200 tonnes). In the same period, other minor producers in Africa recorded slight increases, which include Burundi from 8 700 to 8 800 tonnes, South Africa from 2 200 to 2 500 tonnes and Zimbabwe remained unchanged at 8 500 tonnes (Chang, 2015)

Tea is cultivated for the production of its leaves, which are manufactured into a beverage and is one of the most important beverage crops in the world (Mondal, 2009). Tender shoots of tea consisting of two or three leaves and a bud are harvested periodically to produce either black or green or oolong tea (De Costa*, et al.*, 2007), these being the three main types of *Camellia* tea (Hicks, 2009). The difference lies in the ‘fermentation’, which refers to oxidative and enzymatic changes within the tea leaves during processing (Hicks, 2009). Green tea is essentially unfermented, oolong tea is partially fermented and black tea is fully fermented (De Costa*, et al.*, 2007, Hicks, 2009). Black tea, which represents the majority of international trade, yields an amber coloured, full-flavour liquid without bitterness (Hicks, 2009). South-east Asia (India and Sri Lanka) and eastern and southern Africa (Kenya, Malawi, Zimbabwe, Tanzania, Uganda and Mozambique) are the major producers of black tea, whilst China and Japan are the major producers of green tea (De Costa*, et al.*, 2007).

Tea is a medium to long term cash crop, currently grown in a wide range of climates from Mediterranean-type climates to the hot, humid tropics and includes countries such as Russia and Georgia (42° N) in the northern latitudes to Argentina (27° S) and New Zealand (37° S) in the south. Cultivation also occurs across a range of altitudes from sea level up to approximately 2 700 m.a.s.l. (Carr, 1972, 2010a, Waheed*, et al.*, 2013) covering approximately 52 countries (Mondal*, et al.*, 2004). In central and southern Africa, tea is grown from an altitude of 650 to 1 000 m.a.s.l. (TTC, 2000) (Figure 2.1).


**Figure 2. 1 The major tea producing countries of the world (Source: Njoloma (2012))**

## 2.2 Ecotypes of tea

Commercially grown teas are hybrids of two distinct 'ecotypes', the Assam type (known as Assam jat) and the China type (China jat) (De Costa*, et al.*, 2007). The China type (var. *sinensis*) has small (3-6 cm long) relatively erect, dark green leaves, with a matt surface, whilst the Assam type (var. *assamica*) has larger (15-20 cm long), more horizontally held, light green leaves with a glossy surface (De Costa*, et al.*, 2007). The China type is strongly aromatic, tolerant to drought and can survive short frost periods, however, it is considered to be inferior in both quantity and quality of yield, with the Assam tea being mildly aromatic, sensitive to drought and cold and high yielding (Sigmund and Gustav, 1991, De Costa*, et al.*, 2007, Iori*, et al.*, 2014). While the Assam type is believed to have originated under the shade of humid, tropical forests, the China type is thought to have originated under open conditions in the cool, humid tropics (De Costa*, et al.*, 2007). The variety *sinensis,* also called "China tea", grows well in marginal areas of the subtropics (Iori*, et al.*, 2014). This variation in ecophysiology that exists in the tea germplasm can be used to develop cultivars specifically suited to different climates (De Costa*, et al.*, 2007).

The morphological differences in terms of leaf structure and pose exhibited by these two ecotypes have a strong bearing on the method of harvesting (hand or machine) and on how they intercept light for maximum photosynthesis. The Assam type with its larger leaves, which are horizontal (De Costa*, et al.*, 2007, Bandara, 2012), are designed to intercept as much light as possible, allowing little light penetration to the lower leaves, such that even if photoinhibition occurs in the top leaves the lower leaves will still photosynthesize (Salisbury and Ross, 1992), albeit at a reduced rate. The China type on the other hand has small leaves (De Costa*, et al.*, 2007, Bandara, 2012) that allow maximum light penetration to the lower leaves. The canopy architecture is therefore an important parameter as it determines the crop factor (Kc), leaf area index (LAI) and therefore the interception of photosynthetically active radiation (PAR) required for photosynthesis.

**2.3 Determinants of yield and quality**

In tea, biomass accumulation is the major determinant of yield (Y; g $m^{-2}$) which can be described by the following formula (Burgess and Carr, 1996):

$$Y = S.f_S.\varepsilon_S.HI \quad (2.1)$$

where S is the short-wave solar radiation (MJ $m^{-2}$) incident during the measurement period, $f_S$ is the proportion of radiation intercepted by the crop canopy, $\varepsilon_S$ is the ratio of total dry matter production to intercepted radiation, or radiation use efficiency (g $MJ^{-1}$), and HI is the harvest index, or that proportion of the total dry matter which forms the economic yield. Yield of tea is therefore dependent on a combination of assimilate supply through photosynthesis influenced by radiation intercepted by the crop canopy and formation of harvestable sinks (shoots), and is quantified as the mass of made tea per hectare per year (De Costa*, et al.*, 2007). Made tea refers to the form of tea obtained after the harvested (or plucked) shoot has gone through the manufacturing process (i.e. withering, fermentation and drying) (De Costa*, et al.*, 2007). The mass of made tea is directly related to the fresh mass of the plucked shoot by a factor of 0.225, which is known as a correction factor (CF).

The number of shoots per unit land area has a strong correlation with yield variation and is determined by the rate of shoot initiation, whereas the mean mass per shoot is determined by the rate of shoot expansion (De Costa*, et al.*, 2007). The number of shoots per unit area determines the HI. The greater the shoot number the greater the HI and ultimately the greater the yield. The shoot numbers also influence radiation interception by the crop canopy. The more shoots there are the greater the radiation interception by the crop canopy, increasing photosynthesis and hence assimilate supply. In general the number of shoots per unit land area is responsible for variations in tea yields between different genotypes, whilst the variation in shoot growth rate is the main cause of season-to- season yield variation in a given genotype. Both yield components are influenced by the duration between two successive harvests, referred to as plucking rounds (TRIT, 2002, De Costa*, et al.*, 2007). Increasing the plucking round length from 7 to 14 days doubles the yield, as shoots are harvested after accumulation of sufficient dry matter to contribute to yield (Tanton, 1979). According to Tanton (1979), the expression of yield components is controlled by the environment, management practices and the plant genome and tea yield improvement (in terms of quantity) should be possible by selecting for genotypes which are able to maintain quality parameters in more mature shoots (De Costa*, et al.*, 2007).

The mean mass per shoot is also determined by the plucking standard adopted, i.e. whether two or three leaves and a bud are plucked (De Costa*, et al.*, 2007), which will ultimately impact the quality of leaf harvested. In order to maintain quality characteristics of made tea, shoots have to be plucked at a younger stage (De Costa*, et al.*, 2007). This early plucking of young shoots reduces the sink capacity of the entire bush and reduces biomass accumulation (De Costa*, et al.*, 2007) as the removal of young active sinks leads to negative feedback on photosynthesis, adversely affecting yield. Quality restraints that limit plucking to three leaves and a bud therefore severely restrict yield (Tanton, 1979).

**2.3.1 Biomass production of tea**

The determination of total biomass in mature tea growing in the field is difficult, partly because of the difficulties in recovering all the roots, such that the total biomass production of tea has been estimated to vary from 9.43 to 21.5 t $ha^{-1}$ $yr^{-1}$ (Matthews and Stephens, 1998). This however, is lower than that of other C3 plants (25 - 40 t $ha^{-1}$ $yr^{-1}$) where a vegetative part is harvested. This characteristic of tea is attributed to the continuous plucking of young shoots as yield, because plucking reduces the size of the sink available for storage of assimilates (Magambo and Cannell, 1981). These assimilates are probably utilized to facilitate the observed shoot growth. According to Mohotti and Lawlor (2002) and Bandara (2012), dry matter accumulation depends on the photosynthetic rate per unit leaf area and on the formation of crop leaf area, which in turn depends on the availability of assimilates for their growth (Equation 2.1). The yield of tea is therefore determined by the photosynthetic rate of the maintenance foliage and the rate of extension of the shoot (Manivel and Hussain, 1982a, Okano*, et al.*, 1996, Bandara, 2012). While the leaves are the major organs of photosynthesis, mature brown stems also assimilate $CO_2$, but with low efficiency compared to that of leaves such that on a pruned stem, the newly emerging shoots draw this assimilated starch upwards from the brown stems (De Costa*, et al.*, 2007, Bandara, 2012). Tea is generally associated with low productivity, due to tea possessing the C3 photosynthetic pathway (Roberts and Keys, 1978, De Costa*, et al.*, 2007), which is negatively affected by high temperatures, with photorespiration accounting for 19% of net photosynthesis under normal ambient atmospheric conditions (De Costa*, et al.*, 2007). This high photorespiration results in reduced $CO_2$ assimilation, reduced energy generation, reduced photosynthetic output and therefore reduced shoot growth.

This is mainly because tea is thought to have originated as an understorey plant in the tropical rainforests, with its photosynthetic apparatus adapted to function with maximum capacity under shade (De Costa*, et al.*, 2007). Consequently, maximum light saturated photosynthetic rates of tea are below the average for C3 plants and photoinhibition occurs at high light intensities. Processes such as light capture electron transfer and carboxylation restrict the source capacity of tea (Carr, 2010a). The low photosynthetic activity of tea partly explains why the total biomass and dry matter yields of harvested (plucked) young shoots are relatively small (500 – 2 500 kg $ha^{-1}$ $year^{-1}$), because, in part, harvesting removes much of the active productive area and nutrients (Mohotti and Lawlor, 2002).

Photosynthesis of tea has received less attention than other physiological processes likely to improve production, due to the belief that tea has an inadequate number of growing shoots to use the assimilates produced by photosynthesis, i.e. tea may be ‘sink limited’ because shoots are harvested before their maximum biomass is reached, in order to maintain quality characters of made tea (Tanton, 1979, , Mohotti and Lawlor, 2002, De Costa*, et al.*, 2007). However, it may also be ‘source limited’, because of inadequate assimilate production due to the low rates of photosynthesis compared to other tropical crops (Mohotti and Lawlor, 2002). Sinks are those tissues which are net importers of carbohydrates whilst sources are net exporters of carbohydrates. Young leaves and buds are initially all sinks and typically only once a leaf is fully expanded it becomes a net exporter of carbohydrates. The continued removal of young shoots can also reduce photosynthesis in the source leaves due to a buildup of assimilates in these leaves which leads to a negative feedback on photosynthesis.

### 2.3.2 Factors impacting tea yield and quality

Tea can be grown under a wide range of conditions, but in order to achieve high yields and quality certain requirements must be met, which are broadly fall under environmental/abiotic factors, biotic factors, and agronomic factors. Growth of the tea plant is dependent on many factors, comprising those that are inherent in the plant itself and those exerted on the tea crop by nature, such as soil and climatic conditions, pest and diseases and man through crop husbandry and cultural practices.

#### 2.3.2.1 Environmental/ abiotic factors

##### 2.3.2.1.1 Air temperature

The growth cycle of tea is temperature dependent, when other factors are not limiting, such that shoot growth ceases during the cooler winter months, only to resume in the warmer summer months. Ambient temperature largely affects tea yield and quality by influencing the rate of photosynthesis and through the control of growth and dormancy. Both the shoot extension rate and shoot mass of tea are influenced by air temperature, with air temperatures between 13°C and 28-30°C conducive for growth of tea (De Costa*, et al.*, 2007, TTRA, 2012b). However, night-time temperatures below 10°C lead to reduction in leaf growth rate (Kamau, 2008). Some cultivars like the *sinensis* varieties can, however, tolerate lower temperatures, and may even withstand frost of -5°C, whereas the leaves of var. *assamica* are killed even by the mildest frost (Sigmund and Gustav, 1991, Kumar*, et al.*, 2015). Temperatures above 32°C reduce shoot growth, especially if accompanied by low humidity (De Costa*, et al.*, 2007, TTRA, 2012b). In areas where ambient temperatures exceed 30°C, the cultivation of tea under shade trees like *Falcataria mollucana, Gliricidia maculata or Grevillia robusta* is advisable (Bandara, 2012). These trees create micro-environments under their canopies by reducing air temperature, protecting tea bushes from direct sunlight and maintaining a suitable relative humidity for optimum photosynthesis and hence shoot growth. According to Bandara (2012), shade trees help to conserve soil moisture by 1-3 % during the dry season as they extract soil moisture from different depth and lowers the leaf temperature by 2-4°C.

The minimum temperature at which shoot extension ceases is known as the base temperature and is both cultivar and location dependent (Bandara, 2012). A base temperature of 12.5°C has been reported for cultivar SFS 204 in Malawi, whilst values ranging from 8.9 to 11.3°C have been reported for four different cultivars in Mufindi, Tanzania. In general the base temperature for shoot extension varies between 7°C and 15°C, with an average of 12.5°C (De Costa*, et al.*, 2007).

#### 2.3.2.1.2 Soil temperature

Soil temperature is also reported to influence the growth and yield of tea and also influences the survival of tea (Bandara, 2012). Soil temperature has also been suggested to be an important variable for tea yield, as shoot extension rates are reduced at soil temperatures (0.3 m depth) of below 16°C (Kamau, 2008) and the growth of tea shoots decreases at soil temperatures above 25°C at 0.3 m soil depth. High soil temperatures during the day and low night temperatures induce flowering, leading to poor shoot growth (De Costa*, et al.*, 2007). This is a common phenomenon in PC 108.

#### 2.3.2.1.3 Solar Radiation

Among the environmental factors determining plant growth, interception of solar radiation by the foliage is the main source of energy for the processes of photosynthesis, biomass production, energy balance and the exchange of $CO_2$ and transpiration (Consoli*, et al.*, 2006). The availability of solar radiation can often limit plant recruitment and growth in shaded environments. If nutrients or water are not limiting, then radiation is usually the most important factor influencing the growth and development of plants. Tea is no exception and requires, on average, at least five sunshine hours per day (17 MJ $d^{-1}$). Tea yield drops significantly under cloudy conditions and with heavy and continuous rainfall, as it does under hot and dry conditions (Kamau, 2008), or when the days in winter are too short (Sigmund and Gustav, 1991). Squire (1977), observed that when solar radiation levels at the top of the canopy exceed 350 W $m^{-2}$ single top leaves are photosynthetically light saturated. However, whole tea plant canopies require 700–800 W $m^{-2}$ for optimal photosynthesis. Daily total solar radiation is important in determining shoot growth, as reduced daily total solar radiation reduces the rate of shoot development and extension as seen on cloudy days.

#### 2.3.2.1.4 Rainfall

Tea grows under a wide range of climatic conditions from equatorial to humid, temperate climates, with varieties differing in their tolerance to hardy conditions. The *sinensis* varieties are hardier, tolerate a longer dry season and can exhibit higher water status than the *assamica* varieties under soil water deficits (Kamau, 2008, Kumar*, et al.*, 2015). A minimum annual rainfall of 1 200 to 1 300 mm is necessary for the growth of tea (TRFCA, 2013a, Waheed*, et al.*, 2013), however, for optimum growth and high yields an annual amount ranging between 2 500 and 3 000 mm is ideal (Anandacoomaraswamya*, et al.*, 2000). The even distribution of this rainfall throughout the production season is, however, more important than the total rainfall received annually. At the equator, the ideal monthly rainfall distribution will be 90 to 180 mm, and crop yields fall when monthly rainfall is below 60 mm (Kamau, 2008). In regions where rainfall is less than 1 150 mm per annum, with long and hot dry spells, irrigation is recommended (Carr and Stephens, 1992). Occasionally, severe damage from hail occurs and results in yield losses of 10 to 30% (Kamau, 2008). The atmospheric humidity must be high between 70 and 90%, as shoots tend to form dormant ‘banjhi’ buds when the air is too dry. High atmospheric humidity is particularly valuable during dry seasons and when the annual rainfall is low (Kamau, 2008).

#### 2.3.2.1.5 Altitude

Altitude and topography are important considerations for tea production and call for different cultural practices (Kamau, 2008), such as harvesting, pruning, fertilization, and water and soil conservation measures. Tea plants are capable of being cultivated at varying altitudes, ranging from sea level (as in Japan, Indian and Indonesia) to above 2 700 m (as in parts of Africa) (Kamau, 2008, Willson, 2012). Low-grown teas are produced from 0 to 600 m, mid-grown from 600 to 1 200 m, while the high-grown teas are cultivated between 1 200 and 2 000 m (Hicks, 2009). These differences in altitude have profound effects on the yield and quality of tea. The rate of growth at high elevations is markedly lower than the hot, humid low areas, due to lower temperatures, but these conditions are ideal for the production of high quality tea (Kamau, 2008, Owuor*, et al.*, 2011, Muthumania*, et al.*, 2013, Waheed*, et al.*, 2013). High altitude teas are therefore generally superior in terms of quality (aroma, colour, brightness, mouthfeel, and of course, flavour) than teas from low lying regions (Willson, 2012).

**2.3.2.1.6 Soil**

Tea is produced on a wide variety of soil types derived from a range of parent material (Othieno, 1992), although specific soil characteristics must be met by a particular soil type for successful tea cultivation. These specific characteristics include soil pH and soil physical characteristics, such as soil depth, texture and structure (Kamau, 2008). Most soils used for tea production are highly weathered and leached soils, with a high water holding capacity, such that they retain sufficient water throughout the year. The degree of leaching and hence the character of the resulting soil depends on rainfall, temperature and the age of the soil (Kamau, 2008). Ideally tea requires deep well drained, acidic soils, with pH ($CaCl_2$) levels in the range of 4 to 5.5 (Drinnan, 2008, Sigmund and Gustav, 1991, TTRA, 2012b) and low Ca (Sigmund and Gustav, 1991), with others reporting a pH value as high as 6.0 as being ideal for tea production (Othieno, 1992). Whenever the soil pH range becomes undesirable for tea growth, such as due to acidification as a result of continued and sustained nitrogen fertilization, liming becomes important to correct the soil pH.

The most important soil physical requirement for tea plant production is a deep, well-drained soil. The soil should be approximately 1-2 m deep, with an aggregated or crumb soil structure with 50% pore spaces (Dey, 1969). Soils with poor drainage lead to reduced vigour and yields of tea due to waterlogging (Drinnan, 2008). Tea grows on soils with a texture ranging from sandy loam to clays, including silts and loams of all types, however, the lighter sandier soils are not desirable due to their lower water holding capacity. These soils can, however, be used for tea cultivation provided there is good distribution of rainfall, an irrigation system is installed and if nutrients can be provided on a more regular basis (Kamau, 2008).

#### 2.3.2.2 Biotic factors

##### 2.3.2.2.1 Pests, diseases and weeds in tea

A long-term, i.e. permanent monocultural, crop like tea can be exposed to insect pest infestations and disease infections because it provides a stable micro-climate and a continuous supply of food for pests and diseases (Rattan, 1992). Currently, insect pests and diseases are not a serious problem in tea production in Malawi and Zimbabwe (Rattan, 1992) as compared to other countries in Africa and the world over. Leaf and shoot feeders are the crucial pests in terms of yield reduction and these include, mosquito bug (*Helopeltis* spp.), tea thrips (*Scirtothrips* spp.), mites, aphids (*Toxoptera* spp.), scale insects, and termites. These pests are capable of causing phenomenal losses in crop yields of between 5 and 55% (Hazarika*, et al.*, 2009). Annual yield losses of up to 30% due to mites were reported in Kenya, whilst in Malawi a 55% yield loss due to mosquito bug has been reported (Kamau, 2008, Rattan, 1984). Live wood termites (*Glyptotermes dilatatus* Bug. & Pop) and carpenter moths (*Teragra quadrangula*) can cause serious damage to young tea. Tea of all ages is susceptible to live wood termite attack but it appears that tea in the first 3 years from planting is most vulnerable, with mature tea under heat or water stress also susceptible (Rattan, 1992). Other pests of importance in tea are jelly grabs, stinging caterpillar, red spider mite (*Oligonychus coffeae*), yellow mite (*Polyphagotarsonemus latus* Banks), scarlet mite (*Blevipalpusphornicis spp.*), and black tea thrips (*Heliothrips haemorrhidalis* Bouch) (Lightfoot, 2009).

Since leaves are the harvested product in tea, leaf diseases play an important role and these are easily observed when the tea is under plucking. The severity of the disease is influenced by high relative humidity and is more serious when plants are recovering from pruning (Kamau, 2008). Disease control is therefore critical during the pruning period. The most common diseases of tea in Malawi and Zimbabwe are brown (*Glomerella* cingulate) and grey blight (*Pestalotiopsis theae*), eye spot (*Pseudocercospora ocellata*), damping off (*Pythium spp*) and *Armillaria* root rot (Rattan, 1992, Lightfoot, 2009). Both brown and grey blight affect young and mature leaves, causing lesions, leaf spots and stem dieback. The laceration of leaves reduces the photosynthetic area and hence affects shoot growth. Disease control measures are seldom employed, and spraying of fungicides is unnecessary since the disease attacks weakened or injured bushes, for example, bushes affected by an excessive dose of nitrogen, hail, frost, hard plucking and sunscorch (Rattan, 1992) and therefore the underlying causes should be ascertained and corrective measures taken.

*Armillaria* root rot is only an important disease in areas where tea is planted in virgin lands and when shade trees have been removed without first ringbarking (Rattan, 1992) to ensure that all the roots are dead to avoid tree by tree disease transmission via the roots. The disease destroys the roots so that water and nutrient supply is restricted, resulting in leaf wilting and defoliation and finally death of the bush. Once established, root diseases are difficult to eradicate and appropriate control measures to identify and remove affected bushes in the field in the early stages is important. Other effective methods to control *Armillaria* include the use of *Trichoderma* species and soil solarization (Kamau, 2008)

Weeds are among the critical factors limiting optimum productivity from tea plantations. According to Deka and Barua (2015), the severity of weed infestations is primarily governed by agro-climatic conditions, type of tea culture, general management conditions, and the specific weed management schedule. Dominant weed flora in tea gardens include black jack (*Bidens pilosa*), wandering jew (*Commelina benghalensis*), couch grass (*Cynodon dactylon*) and nut grass (*Cypericea rotundus*) (Lightfoot, 2009). Failure to control weed growth can cause a 50 to 70% loss of tea productivity (Deka and Barua, 2015). Chemical weed control is still recommended, however, growers are encouraged to use Integrated Pest Management (IPM) techniques, so as to prevent overuse of pesticides and subsequent residues in made tea (Hazarika*, et al.*, 2009, Lightfoot, 2009). In line with keeping within the required maximum residue limits (MRLs) only eight chemicals are recommended for use by growers in Malawi and Zimbabwe for the control of pests, diseases and weeds (Vermeulen, 2007, Lightfoot, 2009). These include fipronil for the control of termites, polysulphide sulphur, calcium polysulphide and sulphur for the control of mites, cupric hydroxide and copper oxychloride for the control of fungal diseases, glyphosate and S-metalochlor for the control of post- and pre-emergent weeds (Vermeulen, 2007, Lightfoot, 2009).

### 2.3.3 Agronomic practices impacting on tea yield and quality

#### 2.3.3.1 Planting material and practices

Conventional breeding programmes in most tea producing countries have been designed with the prime objective of increasing yield (Wachira, 1994). Since cultivated tea is maintained as a low bush, in a continuous vegetative phase of growth, and its harvestable produce is purely vegetative, comprising only a small fraction of the total biomass, it is important to use such vegetative characteristics as selection criteria for yield (Wachira, 1994). Initially, tea was grown from seed to produce seedling tea that is heterogeneous due to natural outcrossing, resulting in numerous hybrids referred to as Assam, Cambod or China depending on the morphological proximity to the main taxa (Kamau, 2008). This heterogeneity resulted in variation in yield, quality and suitability for fermentation. The focus thereafter shifted to yield as the main selection criteria. However, over the years, tea selection and breeding programmes have resulted in improved varieties that combine high-yielding ability, good quality, stress tolerance, and pest and disease resistant traits (Kamau, 2008). These selections are vegetatively propagated and are referred to as clonal/cultivar tea. Young plants are produced from cuttings obtained from a selected mother bush (which possess the desired attributes) in the field and carefully tended in special nursery beds until they can be planted out in the field between the ages of 6 to 12 or 18 to 20 months. In east Africa, maximum yields of released cultivars vary considerably from 3 t $ha^{-1}$ for the unselected seedling types to 11 t $ha^{-1}$ for clone AHP S15/10, whilst those in central Africa show a much smaller range between the seedlings (4.2 t $ha^{-1}$), and the clonal cultivars (SFS 204, 5.8 t $ha^{-1}$). Cultivars released from India and Sri-Lanka have maximum yields of approximately 3 t $ha^{-1}$ (Kamau, 2008).

Planting of vegetatively propagated plants should not start until after the main rains have set in (around November) and should cease by mid-February at the latest (Grice, 1990a). This according to Grice (1990a) is the period when sufficient rains have fallen to wet the soil to at least twice the planting depth and when there is a high probability that the rains will continue for some time. Planting distance depends on climate, soil fertility and growth form (Sigmund and Gustav, 1991). The final spacing and population depends on the target yield and the climate prevailing in the given area and different plant spacings are recommended depending on whether the tea is rain-fed or irrigated. According to Grice (1990a) the following spacings have been recommended in central and southern Africa for rain-fed tea: 120 x 90 cm, 120 x 85 cm, 120 x 80 cm, 120 x 75 cm and 120 x 70 cm giving a plant population of 9259, 9804, 10417, 11111, 11905 plants ha$^{-1}$. Under irrigation 120 x 65 cm and 120 x 60 cm was recommended, giving a plant population of 12821 and 13889 plants ha$^{-1}$. A closer spacing of 120 x 60 cm was evaluated in Kenya, where higher yields were obtained in the initial years, however, during drought years yields were negatively affected (Kamau, 2008), thereby outweighing the initial gains. The move to mechanical harvesting has also brought about a modification of the plant spacing where the need for closer spacing and higher shoot densities per plucking point is called for. Plants are planted out in hedges with spacings from 1.8 – 3.6 m between centers with populations of 12 000 to 25 000 plants ha$^{-1}$ (Drinnan, 2008).

#### 2.3.3.2 Bush management – Pruning

Pruning is essentially the removal of all or most of the leaf bearing branches of the plant (Nissanka, *et al.*, 2004) at a pre-determined height and at a specified interval in order to reinvigorate and bring tea bushes within reach of the pluckers (TRIT, 2004, Kumar, *et al.*, 2015). The operation is therefore aimed at keeping the size and vegetative vigour of the plant in a condition most conducive for maximum vegetative growth and cropping (TRIT, 2004). Although pruning puts an immediate check on growth, it will renew the plant and provide the stimulus for vegetative growth to divert stored energy for production of growing shoots. Pruning also corrects past defects in bush architecture, maintains ideal frame height for economic plucking, improves bush hygiene, and reduces the incidence of pests and diseases (Dutta, 2011). Grice (1990c), states that the height of tea under cultivation is well controlled and maintained between 0.60 – 1.00 m to facilitate plucking. The process of pruning is energy consuming and causes a lot of stress on the plant and exposes the frames to the hot sun, thereby predisposing the branches to sun scorch (Grice, 1990c). Recovery after pruning or harvesting depends on the health status of the plant, amount of reserves present and on the process of ageing (Nissanka*, et al.*, 2004, Kamau, 2008).

Yields are generally low during the year following pruning, however, yields tend to increase in the second year after pruning before gradually declining in the third or fourth years. The decline in yield and quality in the third or fourth years is as a result of shoots becoming smaller, an increase in the number of banjhi shoots and the failure of more buds to grow (Nissanka*, et al.*, 2004). To avoid such a scenario pruning is carried out at regular intervals. Different pruning cycles have been recommended for different areas and cultivars of tea (Grice, 1990c). For example in Vietnam and north India pruning is done every year (Kamau, 2008) and after every four years in south India (Dutta, 2011) or 5 years in Darjeeling in India (Kumar*, et al.*, 2015). However other countries/regions like Sri Lanka and east Africa have three to six year pruning cycles, depending on the altitude (TRIT, 2004, Kamau, 2008). In central and southern Africa, including Zimbabwe and Malawi, a two or three year pruning cycle is followed (Grice, 1990c).

Skiffing is often adopted to prolong a pruning cycle (TRIT, 2004). Skiffing is normally a light prune and involves removal of the green wood at about 15 cm above the pruning height (Kamau, 2008). A deep skiff is performed 12-15 cm above the last pruning mark. The deep skiff helps to regulate crop distribution and to reduce the ill effects of drought, excessive creep and the height of plucking table (TRIT, 2004). Skiffing is sometimes performed when the management wants to change from hand plucking to machine harvesting with the aim of levelling the plucking surface (TRIT, 2002). When tea plantation productivity decreases or is degraded due to a combination of factors, e.g. many gaps due to bush deaths, thin and diseased branches, shoots at the base or sprouting from the soil, rejuvenation pruning is recommended (Kamau, 2008). This involves low pruning to remove as much unproductive bush frame as possible, including any remaining diseased parts of the bush (Kamau, 2008). The prunings are left in the fields to act as a mulch and to protect the fields from erosion and maintain soil fertility, since large amounts of N, P and K are returned to the soil through the decomposition of the prunings (Grice, 1981, Kamau, 2008).

Pruning can be done at different stages depending on the growth of the plants and for different purposes. For example, in the nursery, pruning is done to force the plants to form a low frame early in development (TRIT, 2004). In young tea plantations, pruning is done to check the vertical growth habit of tea so that it produces a low, spreading branch structure, in order for the tea canopy to quickly fill the empty space between plants (TRIT, 2004). This is known as formation pruning or bringing into bearing, and stimulates the production of lateral branches. The frame that develops becomes the permanent frame of the bush (TRIT, 2004).

Since pruning removes all the foliage it reduces the capacity of the tea bush to photosynthesize, therefore the most convenient time to perform the pruning operation is during the dormant period, when the starch reserves in the roots are at their highest for fast recovery (Eden, 1965, Kamau, 2008, Kumar*, et al.*, 2015). The winter period (May/June) has been found to be the most suitable period for pruning in Zimbabwe, taking into consideration that the yields will be low, root starch reserves will be high and there is a definite wintering season when labour is available (Eden, 1965, Grice, 1990c). In some situations dry weather pruning reduces transpiration losses and protects the tea from death that occurs in a severe drought (Eden, 1965). According to Nyirenda (2007), when a severe drought is predicted as a result of unusually low average rainfall in February/March, all tea up to 9 years should be pruned to alleviate possible drought effects.

**2.3.3.3 Tea nutrition and fertilization**

As tea is normally grown as a long-term monoculture, soil or foliar fertilizer applications are critical to ensure a continued supply of nutrients from the soil. Without supplemental applications the soil will become exhausted, leading to mineral deficiencies in the plants, severe reduction in yield and, ultimately, to a degraded plantation and death of plants. According to Iori*, et al.* (2014), a decline in productivity can also be attributed to a decline in soil fertility. The main nutrient elements removed from a tea plantation through harvesting are N, P and K (Kamau, 2008). The amounts of N, P and K removed from the tea bush through plucking from studies done in Kenya are shown in Table 2.1. Quantities do, however, vary from one tea producing area to another, and depends on the cultivar and type of plucking (Kamau*, et al.*, 2008). According to Kamau (2008) in Kenya, the N removal as a result of plucking ranges from 40 to 160 kg N $ha^{-1}$, assuming made tea yields of 1 to 4 t $ha^{-1}$.

**Table 2. 1 Macro-nutrient removal (in kg) per 1000 kg made tea (after, Kamau, 2008)**

| N (kg) | P (kg) | K (kg) | References |
|---|---|---|---|
| 40.2 | 3.7 | 13.3 | Eden (1952) |
| 40.0 | 1.7 | 15.8 | Othieno (1979a) |
| 41.5 | 3.5 | 21.6 | Tandon (1993 |

According to Drinnan (2008), nutrition is one of the major factors that can be manipulated to influence the yield, if all other factors are non-limiting. Nitrogen is a critical element in tea production affecting yield and quality. Yields increase with increasing nitrogen application up to high levels, with proportional increases in economic returns (Sitienei*, et al.*, 2013). Annual applications of 250-450 kg N $ha^{-1}$ $yr^{-1}$ are most common (Drinnan, 2008), with rates varying according to age of the tea and location. According to Grice (1990b), the recommended nitrogen application rates in Zimbabwe for optimum yields range from 225- 300 kg N $ha^{-1}$ $yr^{-1}$, split between two or three applications, depending on whether the tea is rain fed or irrigated. In Australia, 250 kg N $ha^{-1}$ $yr^{-1}$ is recommended, split between three even applications in spring and at the start and middle of the wet season. Indonesia uses a rate of 300 kg N $ha^{-1}$ $yr^{-1}$, split into three to six applications and Kenya uses rates of 200 – 400 kg N $ha^{-1}$ $yr^{-1}$ (Drinnan, 2008).

#### 2.3.3.4. Plucking

Plucking is the periodic and skilful harvesting of the targeted young shoots, normally a bud and two to three leaves (TRIT, 2002), above the plucking table and is either done by hand or mechanically. Good plucking practices will aim to strike a balance between yield and quality (Kamau, 2008). Traditionally tea, was harvested by hand, however, due to the sharp rise in labour cost and its scarcity, mechanical harvesting using either machines and/or shears has become a necessity in most tea growing areas (Grice and Clowes, 1990).

The standard of plucking will determine the quality of tea which can be produced, and the cost of plucking will have a major impact upon the profitability of the enterprise (Ravichandran and Parthiban, 1998, TRFCA, 2010). Fine plucking, that is, no more than two leaves and an unopened bud, provides the basis for quality tea (TTC, 2000). In order to achieve this high standard of leaf, plucking should be done at regular intervals, known as plucking rounds. The length of the plucking rounds are adjusted according to the rate of shoot growth and this differs during the year as a result of fluctuating temperature (TRIT, 2002). In Malawi and Zimbabwe, short plucking round lengths of 10/11 days are recommended for the highest yield and quality under hand plucking for most of the year, whilst longer 14 day rounds are recommended for mechanical harvesting to maximize both yield and quality (Grice and Clowes, 1990, Madamombe, 2008). However, in Kenya shorter plucking rounds of 7 – 10 days result in optimum yields and black tea quality (Kamau, 2008).

Harvesting removes the photosynthetically active green tissue and apical dominance. Once apical dominance is broken by plucking, one or two axillary buds below the plucking point start swelling and regeneration of new shoots starts (De Costa*, et al.*, 2007). These tender shoots are periodically harvested as yield when they have developed two or three leaves and a bud. As a result, production, partitioning and utilisation of assimilates, which determine the growth and vigour of the tea bush, are largely influenced by plucking policies. Appropriate plucking policies should, therefore, be adopted to generate higher yield with enhanced labour productivity, while ensuring the quality of end product and productivity of the tea bush. Thus to maximize productivity, pruning and plucking must be synchronized to stimulate re-growth (Kamau, 2008).

Numerous studies have been conducted at a number of tea research institutes on the physiology of shoot production, leading to a scientific understanding of plucking rounds, and the ability to optimize production from an agronomic point of view. However, the study of different plucking methods is an area where results become less clear cut, since there are many interacting factors involving management and remuneration issues, which vary from location to location (TRFCA, 2010). The climate, the bush, the shoot and the plucker all affect plucking management. The climate influences growth rate, the bush produces the shoots that are to be plucked and the plucker has the responsibility of harvesting the raw material that make the finished product – tea (Grice and Clowes, 1990).

## 2.4 Tea harvesting methods

In order to maximize yield components by maintaining source and sink relationships and the health of the bush, selection of proper harvesting policies is necessary. These plucking policies include methods, standards, severity and frequency of harvesting and they differ from one estate to the other, depending on the management practices and the type of tea produced. Nevertheless, the best plucking policy is one that gives the highest productivity at a low cost, while ensuring the quality of the end product and vigour of the tea bush (Wijeratne, 2003).

### 2.4.1 Standards of plucking

Standard of plucking denotes the type of shoot harvested. Depending on the length of plucking round, or the type of shoots harvested, five standards of plucking were identified in India (Table 2.2) (TTRA, 2012a) and three (fine, medium or coarse) in Sri Lanka (Wijeratne, 2003). Accordingly, when the majority of plucked shoots comprise two leaves and a bud, it is called fine plucking. Standard plucking consists of one large leaf and a bud, all two leaves and bud, three small leaves and a bud and soft single banjhis. If the harvested crop consists of equal proportions of shoots with two and three leaves, it is considered as medium plucking. Coarse plucking implies the presence of a higher proportion of shoots with more than three leaves, together with other mature dormant shoots (Wijeratne, 2003). Black plucking is plucking all shoots at the plucking table and leaving behind only unopened buds (TRIT, 2002). In Malawi and Zimbabwe standard plucking is the most acceptable and profitable in terms of yield and quality (TPH, 1990).

**Table 2. 2 Plucking standards associated with harvesting of tea (Adapted (TTRA, 2012a)**

| System name | Shoot size | Plucking round (days) | % crop gained/loss over standard plucking |
|---|---|---|---|
| Fine | 1 + B[†]; small 2 + B | 5/6 | - 11.3 |
| Standard | Large 1 + B; all 2 + B small 3 + B & single banjhis | 7 | Base |
| Medium | All 2 + B; 3 + B; single and double banjhis | 7/8 | + 0.5 |
| Coarse | 3 + B or larger shoots all banjhis | 8 or more | + 28.2 to 38.4 |
| Black | All 1 + B; 2 + B and single banjhis | 6/7 | - 5.0 |

[†] B = bud

In order to make good quality black tea, a mixture of two or three leaves and a bud are required, as these contain the highest proportion of the required chemical compounds (Theaflavins (TF), Thearubigins (TR), caffeine and catechins required for good quality tea. To maintain a balance between quality and yield, 75% fine, which should include a bud and two leaves and soft banjhi (undeveloped bud and two leaves) and 25% coarse leaf in the harvest is ideal (TTRA, 2012a).

There is continual conflict between the requirements to harvest the maximum amount of leaf, and maintaining the acceptable plucking standard (Kilgour and Brighton, 1999). Methods of plucking broadly fall into two categories, hand plucking and mechanical harvesting, each with a range of sub-categories which are outlined below.

### 2.4.2. Hand plucking

The traditional way of harvesting tea is by hand plucking (Kilgour and Brighton, 1999), which is a relatively uniform and selective method, which maintains high made tea quality (Figure 2.2). There is better selection of fresh young shoots, leaving mature shoots and immature buds on the plant, ensuring high quality tea (Bandara, 2012). It is a skilled job to pluck the two or three leaves and a terminal bud, maintaining a uniform plucking table and allowing a recommended creep (table rise) per year (Kilgour and Brighton, 1999).

According to Kilgour and Brighton (1999), hand plucking is relatively slow and thus labour intensive. Plucker productivity is estimated to be between 45 to 70 kg green leaf day$^{-1}$ depending on the flush (Louis and Mudau, 1999), with Zimbabwe averaging 70 kg green leaf day$^{-1}$ on most estates (TTC, 2015). On average about 21 people (shifts) are required to harvest a hectare.

However labour has become scarce and in response to these labour shortages, alternative-plucking methods have, therefore, been used in order to keep the tea industry viable. For example, shears have been used in Japan since the early 1900's (Kilgour and Brighton, 1999), when labour moved from tea plucking, which was not an attractive job for young people, to the more lucrative motor industry (Shimomura, 1999).

**Figure 2. 2 Hand plucking at Tea Research Foundation of Central Africa, Malawi**

### 2.4.3 Mechanical harvesting

The quest to find suitable harvesting methods which are fast, cheap, can maintain a plucking standard, and results in high yield and quality is what has generated the interest in research on mechanical harvesting of tea (Kilgour and Brighton, 1999). Mechanization of tea harvesting, although not new to southern Africa, is still in its infancy. Most of the estates adopting these techniques are using simpler types of machines. Where manual labour is in short supply (as is the case in Zimbabwe) and/or expensive (as is the case in South Africa) (Nyasulu, 2006), the failure to attract the required number of pluckers meant that some estates, especially in Zimbabwe, introduced machine plucking on a large scale, in the late 1990s. In South Africa, Senteeko estate introduced mechanical harvesting as early as 1977/1978 (Steenkamp, 1999).

Mechanical harvesting methods offer the possibility of increasing worker productivity, thereby reducing the cost of harvest per kg of tea. Harvesting machines are, however, part of a total production system, and must be compatible with the production cycle of the tea bush, the skills and support services available for their sustained operation and maintenance, as well as being economically and socially viable in the long term (Kilgour and Brighton, 1999).

They are two sub-categories of mechanical plucking methods viz: 1) a semi-mechanical method, i.e. shear plucking, in the sense that the method is not motorized and relies on manual operation, and 2) the fully motorized tea harvesters which consist of motorized reciprocating blades or have primary top blade cutter bar movements. Fully mechanized harvesting involves the use of mechanically operated / self-propelled machines.

#### 2.4.3.1 Shear plucking

This is the next step from hand plucking, involving individual manual operation of shears for tea harvesting. Shears are semi–mechanical equipment (Figure 2.3), relying heavily on human skill. As an alternative method to hand plucking, shear plucking is not a recent innovation (Nyasulu, 2001). They have been used for some time by certain estates in Zimbabwe, and for longer periods elsewhere, such as in Japan around 1900 and in Assam as early as 1887 (Kilgour and Brighton, 1999, Wilkie and Malenga, 1995). Most of the estates in central and southern Africa started with the use of shears in 1992/1993 (Wilkie, 1995). The primary motivation for interest in shear plucking was productivity. The majority of users reported substantial gains in productivity, with gains of up to 30% achieved in comparison with hand plucking, and even gains of 50% not uncommon (Wilkie, 1995). Significant variation in productivity has, however, been reported, and in one case productivity was substantially unchanged, indicating the need for careful consideration of management and incentive implications when making a change, in the light of individual estate practices. On average each person can harvest between 110 and 150 kg green leaf day$^{-1}$, with 13 people required to harvest a hectare (TTC, 2000, 2013).

**Figure 2. 3 Shear plucking at Tingamira Estate (Photo: Madamombe G, 2010)**

Shear plucking can also be used to harvest more mature leaf in cases where normal plucking rounds have been missed. They can also facilitate plucking of small shoots that are not necessarily over-matured, like in the case with China type seedling tea. In most cases shears are used during the main growing season November/December until May in Malawi and August/September to May under irrigation in Zimbabwe (Wilkie, 1995), withdrawing during the dry periods with low production.

However, the selectivity in plucking is lost with shear-harvesting and enormous mechanical injury is caused to the harvested leaf. Shear harvesting throughout the year has also been found to deplete root reserves significantly (UPASI, 2000) and reduce the load of maintenance foliage, thereby affecting the leaf:stem ratio. This has a negative impact on yield as there is a linear relationship between maintenance leaf load and yield (UPASI, 2000). The depression of yield under continuous shear harvesting was therefore attributed to the reduced amount of maintenance foliage, increased respiratory loss, low level of carbohydrates in the roots and an imbalanced promoter:inhibitor ratio in mature leaves (UPASI, 2000). According to Ravichandran and Parthiban (1998), this leads to deterioration of tea quality and hence price and profitability. At the same time there are questions as to what level of improvement may realistically be expected, and what sacrifices may have to be made in terms of production levels and quality.

#### 2.4.3.2 Hand held machines

Hand-held machines (HHM) are being used by several estates, more so where there is a hilly terrain and therefore unsuitable for wheeled harvesters, e.g. in Eastern Highlands Plantations Limited (EHPL) in Zimbabwe. These are, however, now a common feature on most estates in Zimbabwe, even where the terrain is relatively flat. The common models used are either the Ochiai or the Kawasaki H140D, with a 1.2 or 2.4 m width reciprocating blade (Figure 2.4). The machines use a 0.5 h.p. 2 stroke petrol engine, with a fuel consumption of 4 L per day.

**Figure 2. 4 The hand held machine at Tingamira estate (Photo: by Madamombe G, 2013)**

The hand-held machines require a team of four people, three people working on the machine and one person to carry the leaf to the weighing and collection points. With these machine up to 1 200 kg green leaf day$^{-1}$ can be harvested, covering approximately 1.2 ha day$^{-1}$ when on round. Each person therefore harvests 300 kg green leaf day$^{-1}$ with the machine harvesting the equivalent of 16 hand pluckers. The disadvantage of these machines is that it is difficult to maintain a good plucking table as the machine relies entirely on the operators to control the height of the cut, because operators tend to carry the machine at a convenient height rather than at the required table height. Therefore it requires good training and skill for satisfactory results. When carried too low, the maintenance leaf is plucked, thereby reducing tea quality and causing stem and twig die back.

#### 2.4.3.3 The Jachacha"*rickshaw*" tea harvester

The Jachacha "*richshaw*" tea harvester appeared on the estates during the early to mid-1990s (Figure 2.5). They were locally made by P & R Engineering, Mutare, Zimbabwe. They are usually operated by a team of four workers, two to pull or push the machine, one to change the bags and one to carry the cut leaf to the weighing and collection point

(Madamombe, 2008). One machine can harvest between 1 200 to 1 500 kg day$^{-1}$ (Stone, 1999), with maximum yields of 2 000 kg green leaf day$^{-1}$ recorded on rare occasions. Each machine can harvest between 1.5 and 2 ha day$^{-1}$, depending on the operating width, e.g. the output of a 1.2 m wide machine is 1.68 ha day$^{-1}$ (de Jong, 1998). According to Stone (1999), each Jachacha replaces about 20 hand pluckers during good flushes and this leads to less estate overheads in the form of housing and amenities and smaller numbers of pluckers to manage. The machine's two wheels, cutter bar and leaf conveyor belt are driven by a 3.5 h.p. 2 stroke Briggs and Straton engine (Mukumbarezah, 2001)

**Figure 2. 5 The two wheeled Jachacha "rickshaw" machine (Stone, 1999)**

In an effort to overcome the labour shortage and improve productivity, Southdown estate tried using oxen-drawn Jachacha in 2008 (personal observation, January 2008) (Figure 2.6). However, productivity did not improve and less than 1 200 kg green leaf was harvested per day, compared to the average of 1 500 kg green day$^{-1}$, due to continuous breakages of the Jachacha, which were not designed for oxen. The increase in down time meant that on average only a maximum of four working hours were achieved per day. Management also faced resistance from workers when they were assigned to Jachacha, as they were now being associated with oxen.

**Figure 2. 6 Oxen-drawn Jachacha at Southdown estate, Chipinge, Zimbabwe (Photo: by Madamombe, 2008)**

The main disadvantage with the hand-held and Jachacha machines is that they require many people per machine and thus they fail to have a significant positive effect on labour savings. New and more robust machines, like the ride on self-propelled machines, which are operated by a single person had to be developed, in order to save labour for other operations.

### 2.4.3.4 The ride-on self-propelled tea harvester

The ride-on self-propelled machine / tea harvester (ROM) (Figure 2.7) is a modified Jachacha "*rickshaw*" tea harvester (Figure 2.5). These machines are especially suitable in areas where the land is relatively flat and they have been widely used in Argentina, Brazil, Japan and Australia.

**Figure 2. 7 Ride–on self-propelled tea harvester at Tingamira estate (Photo: by Madamombe, June 2011)**

The tea harvester is capable of harvesting between 4 000 and 5 000 kg green leaf $day^{-1}$ with only one operator. However, each machine has a team of five people, the driver and four loaders. The ride-on machine replaces almost the equivalent of 40 hand pluckers. Each machine covers 10 to 12 ha $day^{-1}$ using 10 L of diesel $day^{-1}$, powered by a 4 h.p. diesel engine.

It is important to note that the adoption of mechanical harvesting should not imply a decline in green leaf quality. Mechanical harvesting, properly done and managed can produce high quality green leaf compared to manually plucked leaf and without doubt, much better compared to that produced by shear plucking or by using hand drawn machines (Navajas, 1999).

**2.5 Tea Production in Zimbabwe**

Commercial tea production in Zimbabwe started in 1924, when two Assam planters, Arthur Ward and Grafton Phillips, using seeds carried back from Assam by Mrs Florence Phillips, established a small tea plantation, on what is today New Year's Gift estate under

Tanganda Tea Company, in the Chipinge district of the Eastern Highlands of Zimbabwe (Mtisi, 2003, TTC, 2000). Tanganda Tea Company was for 30 years the only tea producing company in the country until it was joined by Southdown Holdings in Chipinge, Eastern Highlands Plantations Ltd and Aberfoyle Plantations in Honde Valley, Hauna districts in the 1950s and 1960s. TILCOR (now ARDA) started Katiyo Tea Estate also in the Honde Valley (Mtisi, 2003). The tea growing areas are located in the Honde Valley and Chipinge districts in agro-ecological region 1 (Figure 2.8), covering 14 439 km$^2$, which translates to almost 4% of the whole country (Mugandani, *et al.*, 2012). The area lies between 24-27$^o$ N latitude and 88-95$^o$ longitude. Zimbabwe has approximately 8 000 ha under tea, producing 18 000 million kg of black tea annually. There is good internal demand for tea and exports fluctuate between 65 and 80%, with the major export destinations being the United Kingdom and United States of America (SNV, 2011).

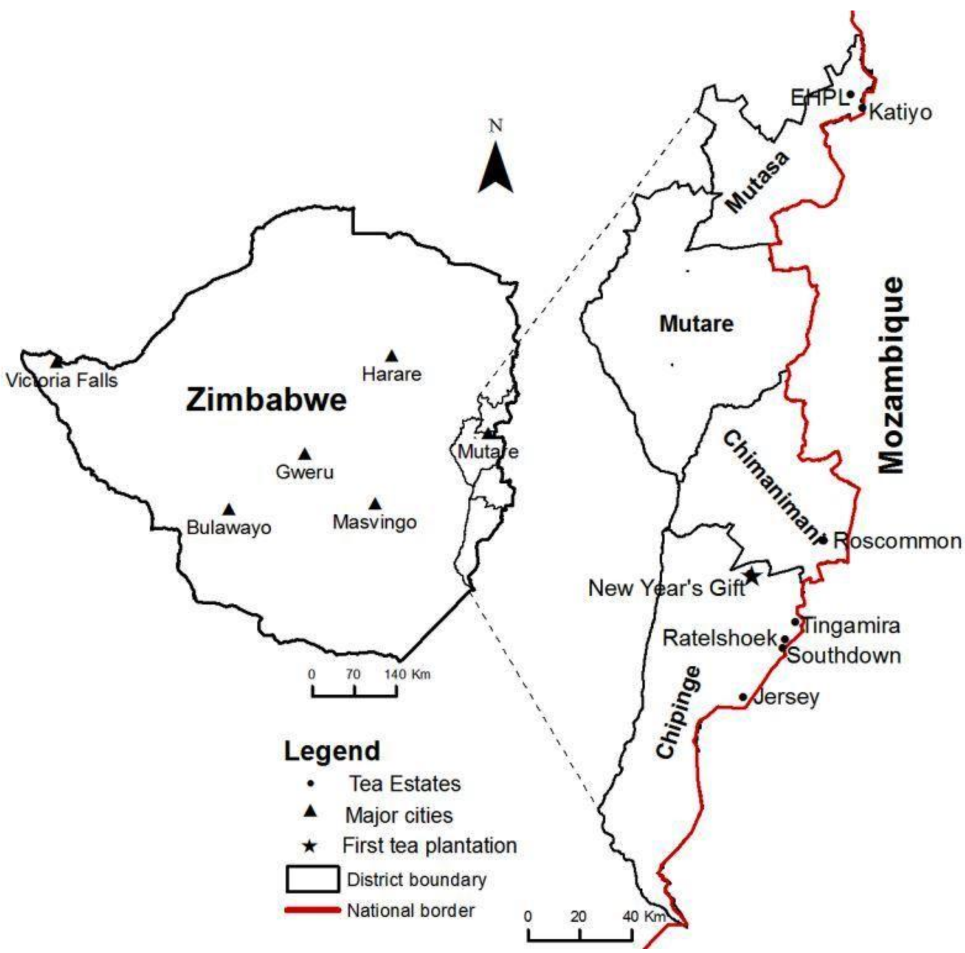


**Figure 2. 8 Tea growing regions of Zimbabwe**

Tea is not indigenous to Africa and its natural habitat is confined to a comparatively small part of the Far East. In southern Africa, few areas enjoy all the ideal conditions of tea's natural habitat, which include high rainfall, lower ambient and soil temperature and high humidity. This does not mean that tea will not grow under conditions which are less than ideal, as research can, to a large degree, overcome most problems of tea culture (TTC, 2000).

### 2.5.1 Temperature

In Zimbabwe's tea growing areas of Chipinge and Honde valley districts, air temperature ranges from 19°C to 23°C, with absolute temperature reaching approximately 10°C in the cool season and above 30°C in the hot, dry season (TRFCA, 2013a). Studies in Zimbabwe showed that an increase in average maximum daily temperatures decreased yields, similarly an increase in monthly total heat units reduced yields (Madamombe*, et al.*, 2010). This is expected for tea growing under rain fed conditions in the hot, dry months of the year, September to November, before the rainy season, as the vapour pressure deficit is normally high and tea bush growth ceases and productivity is reduced (De Costa*, et al.*, 2007, Carr, 2010b, Madamombe*, et al.*, 2010).

### 2.5.2 Rainfall

A minimum annual rainfall of 1 300 mm is experienced in this area (TRFCA, 2013a), however, as mentioned above, it is the distribution of rainfall throughout the season that is more important than the total amount for sustained high yield of tea (TTRA, 2012b). Annual rainfall below 1 000 mm reduces tea yields and makes supplementary irrigation necessary to maintain high yields. This is especially true in southern Africa as the rainfall is seldom well distributed. This is in contrast to the wet conditions prevailing in the tea growing areas of countries like India, Kenya and Sri Lanka (TTC, 2000). The drier conditions in southern Africa impact the growth and quality of tea, such that 80% of the volume of teas in Malawi and Zimbabwe are plucked between December and April and the remaining 20% from May to November (TRFCA, 2013a). Accordingly, the growth rate of tea bushes in the wet season is fast, resulting in low densities of manufactured tea (heavy teas are produced), in contrast to the growth rate of tea bushes in the dry season which is slow and manufactured tea has a high density (lighter teas) (TRFCA, 2013a). In the tea industry density is the volume over a specific mass (usually 100 g in the standard test used) (Jose, 2000). In Zimbabwe very little tea is produced during the dry months of June to August, which are cooler and characterized by shorter day lengths, which reduces growth as shoot extension rates are slow (Carr, 2010b). Conversely, during the warm, wet months of November to April, tea is prolific in its growth (TTC, 2000) and the greatest production occurs during this period, with yields of up 7 000 kg $ha^{-1}$ $yr^{-1}$ of made tea easily achieved.

### 2.5.3 Soil

In Zimbabwe most of the soils in the tea growing areas are orthoferralitic (sandy clay loam) derived from mafic rocks (Chenje*, et al.*, 1998) with an average pH of 4.1. These soils are largely acidic as a result of deep weathering of the underlying rock, followed by intense leaching of bases facilitated by high rainfall, greater than 1 000 mm (Nyamapfene, 1991). They contain few weatherable minerals and are often rich in Fe and Al oxide minerals (Chenje*, et al.*, 1998). Typical profiles are normally very deep, greater than 2 m, and having a high porosity (Nyamapfene, 1991). Owing to their relatively poor nutrient status, high levels of Al and acidic nature, together with substantial slopes characteristic of the areas of Orthoferralitic soils, they are not used for normal cultivation and are largely taken up by plantation tree crops, such as tea, coffee and forestry (Nyamapfene, 1991). The successful cultivation of tea in Chipinge is mainly because tea is well known to be an Al accumulating plant that grows well in strongly acidic soils containing high levels of $Al^{3+}$. According to Morita*, et al.* (2011) the tea plant takes up Al throughout its life span and mature leaves contain up to 30 000 mg Al $kg^{-1}$ of Al on a dry mass basis, without experiencing Al toxicity, mainly because of the ability of tea to detoxify Al.

### 2.5.4 Altitude

In Zimbabwe, tea is grown between altitudes of 650 to 1 000 m.a.s.l., which is within the range reported for tea of 700 to 2 700 m.a.s.l. (Kamau, 2008, Willson, 2012). Studies in Zimbabwe have shown that yield decreases significantly with increasing altitude (Madamombe*, et al.*, 2010). As temperature drops with increased altitude, growth of tea bushes is reduced and consequently yield declines. At lower altitudes, the tea will grow too fast in summer (giving poor quality) and need a lot of water. However, at higher altitudes, the tea will grow slowly, but will be of good quality and less affected by the dry weather, because of cooler temperatures and higher humidity.

Other important agronomic factors impacting yield and quality in Zimbabwe include the planting material (clonal or seedling), method of plucking and nitrogen fertilization. Clonal teas produce high yields of good quality tea, compared to seedling teas, whilst hand plucking is believed to produce higher yields and quality compared to machine harvesting. Increased nitrogen applications result in increased yields, with levels of between 225 and 300 kg N $ha^{-1}$ $year^{-1}$ being recommended (Grice, 1990b, Madamombe*, et al.*, 2010).

**2.6 Mechanical harvesting in Malawi and Zimbabwe**

Since the early 1990's the tea industry in central and southern Africa has considered mechanical harvesting of tea key to address the labour shortage problems in Zimbabwe (Madamombe, 2008). When estates resorted to machine harvesting many questions remained unanswered concerning mechanical harvesting, leading to numerous studies from 1998 to 2004 in Zimbabwe and Malawi to generate local information on mechanical harvesting, and in particular, how to minimize the widely reported negative effects of mechanical harvesting on yield and quality (Madamombe, 2008).

The results from studies in both Malawi (Nyasulu, 2006) and Zimbabwe (Madamombe, 2008) showed that mechanical harvesting reduced the yields and quality of tea. In Zimbabwe a 14.8% yield reduction was observed on clonal tea (SFS 150) when machines were used on a 14 day round and 40.9% yield reduction when used on a 10/11 day round (Table 2.3). There was a yield gain of 2% when the plucking round length was increased from 10/11 days to 21 days with machines (Madamombe, 2008). On Indian seedling tea, a 15.5% yield reduction was observed on a 14 day round and a 41.5% yield reduction on a 10/11 day round (Table 2.4) (Madamombe, 2008). On both types of teas, green leaf quality was poor on the longer 21 day round, but very good on the shorter 10/11 day rounds (Madamombe, 2008).

**Table 2. 3 Percentage mean yield loss on SFS 150 under machine harvesting at Clearwater Estate, Chipinge, Zimbabwe (after, Madamombe, 2008)**

| Treatments | Mean Yield loss (%) |
|---|---|
| **MP 10/11 R2[†]** | **40.90a*** |
| MP 10/11 R3 | 28..95b |
| MP 10/11 R4 | 25.11bc |
| MP 21 R | 23.91bc |
| MP14 R2 | 19.40cd |
| **MP 14 R3** | **14.83d** |
| MP 21 R2 | 13. 29d |
| MP 14 R4 | 11.57d |
| MP 21 R3 | 1.33e |
| **HP 10/11** | **0.00e** |
| MP 21 R4 | - 1.80e |

**[†] MP 10/11 R2 – Machine plucking after every 10/11 days raising the cutting blade after every second round of plucking at the same plucking level**
**HP- Hand plucking**
*** Means followed by the same letter are not significantly different from each other at $p<0.05$ Duncan's Multiple Range Test (DMRT)**

**Table 2. 4 Percentage mean yield loss on Indian seedling tea under machine harvesting at Clearwater Estate, Chipinge, Zimbabwe (after Madamombe, 2008)**

| Treatments | Mean Yield loss (%) |
|---|---|
| **MP 10/11 R[†]** | **41.53a*** |
| MP 14 R | 29.16b |
| MP 10/11 R2 | 29.15b |
| MP 10/11 R3 | 23.73b |
| **MP 14 R2** | **15.49c** |
| MP 21 R | 12.74c |
| MP 21 R2 | 3.50d |
| **HP 10/11** | **0.00d** |

**[†] MP 10/11 R – Machine plucking after every 10/11 days raising the cutting blade after every round of plucking at the same plucking level**
**HP- Hand plucking**

In Malawi, in the second year of mechanical harvesting trial, Nyasulu (2006) reported yield losses of up to 7% on the cultivar PC 108. However, on China seedling tea yields were initially higher (28%) under mechanical harvesting compared to hand plucking, with yields normalizing after two to three seasons. Nyasulu (2006), attributed the widening gap between the plucking methods to the non-selective harvesting of machine plucking on the tea bush.

Harvesting machines have also been shown to reduce the quality of green leaf (Fay, 1950). However, studies in South Africa and Zimbabwe on mechanical plucking showed that mechanical plucking can produce good yields and /or high quality green leaf as compared to hand plucking, depending on how well the machine and the rounds are managed (Mukumbarezah, 1999, Steenkamp, 1999). The long 21 day plucking rounds were shown to produce poor green leaf quality, whereas, the short 10/11 day plucking rounds with machines produced good leaf quality (Madamombe, 2008). The differences in green leaf quality was attributed to the harvesting of many immature shoots under the 10/11 day round, as compared to the long 21 day round, where many over-grown shoots were harvested, leading to a high percentage of bad leaf (Madamombe, 2008).

It was against this background of the results from the experiments in Zimbabwe and Malawi, which did not fully explain why continuous use of machine harvesters on tea decreased yield and quality, that the need was identified to perform further studies. Studies were required to explain how changes in the physiology of the tea bushes result in the progressive and gradual decline in yield and quality, as observed in the cultivar PC 108 (Nyasulu, 2006, Madamombe, 2008). It is important to understand that mechanization is not a single operation concerning only harvesting. The management of the tea bush (fertilization, irrigation and harvesting) and the behaviour of the plant itself are both modified when mechanical harvesting is adopted (Navajas, 1999).

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# CHAPTER 3

## General Materials and Methods

This chapter is a compilation of all the materials and methods in this thesis. It is applicable to all research chapters and is provided to avoid unnecessary repetition in each chapters since some of the chapters share the same materials and methods. This includes the description of the study site, the various harvesting treatments, weather data, yield and yield component determination and how the various data generated was analysed**.**

### 3.1 Study site description

The trial was conducted at Tingamira Estate (Section 8) (Figure 3.1), Chipinge district, Manicaland province, south eastern Zimbabwe (20°09.13′S, 32°48.26′E, 979 m.a.s.l) on the tea (*Camellia sinensis* (L) O. Kuntze) cultivar PC 108. Tingamira Estate is located 30 km from Chipinge town along the Eastern Border road, leading to Mozambique.


**Figure 3.1 Mechanical harvesting trial site at Tingamira estate, Chipinge, Zimbabwe (Google Earth Pro, 06 July 2010)**

The study was conducted over a three year period from the 2010/2011 to 2012/2013 seasons. The bushes were 13 years old at the start of the trial. The field was rain fed, with supplementary irrigation applied during the dry month periods. Irrigation was applied at 50% moisture depletion from the allowable 202 mm total available moisture (TAM) from 0.2 m soil depth. Evaporation readings were taken from an evaporation pan on a daily basis and readings deducted from the TAM until 50% moisture depletion, when irrigation was applied. The daily evaporation figures were multiplied by a pan factor (Kp) of 0.8 to determine the total daily water lost from the crop. A total of 40 mm was applied per irrigation event. The average annual rainfall for the region is 1 208 mm, with a mean annual temperature of 21.2°C, with a mean maximum and minimum temperature of 26.8°C and 15.6°C respectively.

### 3.2 Experimental design

This study, using a 2 x 3 factorial plus added control experiment aimed to study the causes of yield and quality decline in vegetatively propagated cultivar tea under continuous mechanical harvesting. The experiment consisted of three harvesting methods (hand plucking (HP) where harvesting was done after every 10/11 days, and hand-held machine (HHM) and ride-on machine (ROM), where harvesting was done after every 14 days) and three fertilizer levels (265, 300 and 400 kg N $ha^{-1}$ $yr^{-1}$) replicated three times. The Ochiai, hand-held machine, (Ochiai Cutlery Manufacturing Co Ltd, Kikugawa City, Shizuoka Japan, approximate cost between $1 250 and $2 500) (Figure 3.2A) and a ride-on self-propelled machine (Brownes Engineering, Harare, Zimbabwe, approximate cost $10 000) (Figure 3.2B) were used throughout the study period. Height adjustment on the HHM depended on the height of the operators, however, it was maintained by the use of harnesses to help lift the machines, whilst height adjustment on the ROM was set by raising the cutter bar using graduated markings on the sides of the machine.


**Figure 3.2 Mechanical harvesting machines, which included (A) the hand-held Ochiai, and (B) the ride-on self-propelled tea harvester.**

Hand plucking at the lowest fertilizer rate of 265 kg N $ha^{-1}$ $yr^{-1}$ is the standard practice on estates and therefore was used as the control. The reasons for the choice of the rates are as follows: 265 kg N $ha^{-1}$ $yr^{-1}$ is the average current rate applied on estates, 300 kg N $ha^{-1}$ $yr^{-1}$ is the rate recommended by TRFCA for clonal/ cultivar tea (TPH, 1990) and the 400 kg N $ha^{-1}$ $yr^{-1}$ is the rate recommended for mechanical harvesting in Australia (Drinnan, 2008). The fertilizer was applied in three split applications: 46% of the total nitrogen for the whole season was applied in July/August of each year or depending at the onset of the first rains, 27% after first peak (October/November), and 27% after second peak (December/January) (Table 3.1). The split applications were based on the recommendation by TRFCA under rain fed tea cultivation (TPH, 1990).

**Table 3. 1 Programme for applying N (kg N $ha^{-1}$ $yr^{-1}$) in three split applications during a production season**

| Harvesting Treatment | 1st Application (kg N $ha^{-1}$ $yr^{-1}$) (46%) | 2nd Application (kg N $ha^{-1}$ $yr^{-1}$) (27%) | 3rd Application (kg N $ha^{-1}$ $yr^{-1}$) (27%) |
|---|---|---|---|
| **Hand plucking** | 121.9 | 71.6 | 71.6 |
| **Hand-held machine** | 121.9 | 71.6 | 71.6 |
| **Hand-held machine** | 138.0 | 81.0 | 81.0 |
| **Hand-held machine** | 184.0 | 108.0 | 108.0 |
| **Ride-on machine** | 121.9 | 71.6 | 71.6 |
| **Ride-on machine** | 138.0 | 81.0 | 81.0 |
| **Ride-on machine** | 184.0 | 108.0 | 108.0 |

Percentage composition, on a mass basis, of the Tea blend fertilizer (ZFC Limited, Coventry, Workington, Harare) used was: 29% N, 8% K, 12% P, 1% S, 0.05% B, and 0.1% Zn. The fertilizer application dates varied across years, as shown in Table 3.2, with the first application performed soon after the first rains.

**Table 3. 2 The dates on which N was applied to the treatments at Tingamira estate from the 2010 to 2013 season**

| Seasons | Application Times | | |
|---|---|---|---|
| | 1st application | 2nd application | 3rd application |
| **2010/2011** | 5 October 2010 | 27 November 2010 | 18 February 2011 |
| **2011/2012** | 18 August 2011 | 10 November 2011 | 16 February 2012 |
| **2012/2013** | 16 September 2012 | 21 December 2012 | 08 February 2013 |

The fertilizer was broadcasted manually between the rows in a 0.45 m wide strip. The field was rain fed, but supplemental irrigation was applied as needed, as described by Madamombe*, et al.* (2015). Weeds were removed manually both from within and between rows on a regular basis. Plucking rounds were according to standard management practices and are based on a compromise between yield and quality for each harvesting method. The treatment combinations for the experiment are as shown in Table 3.3.

**Table 3. 3 Treatment combinations for the experiment at Tingamira estate**

| Treatment number | Plucking method | Fertilizer rate | Treatment combination |
|---|---|---|---|
| 1 | Hand Plucking | 265 kg N $ha^{-1}$ $yr^{-1}$ | HP 265 kg N $ha^{-1}yr^{-1}$ |
| 2 | Hand-Held Machine | 265 kg N $ha^{-1}$ $yr^{-1}$ | HHM 265 kg N $ha^{-1}yr^{-1}$ |
| 3 | Ride-on Machine | 265 kg N $ha^{-1}$ $yr^{-1}$ | ROM 265 kg N $ha^{-1}yr^{-1}$ |
| 4 | Hand-Held Machine | 300 kg N $ha^{-1}$ $yr^{-1}$ | HHM 300 kg N $ha^{-1}yr^{-1}$ |
| 5 | Ride-on Machine | 300 kg N $ha^{-1}$ $yr^{-1}$ | ROM 300 kg N $ha^{-1}yr^{-1}$ |
| 6 | Hand-Held Machine | 400 kg N $ha^{-1}$ $yr^{-1}$ | HHM 400 kg N $ha^{-1}yr^{-1}$ |
| 7 | Ride-on Machine | 400 kg N $ha^{-1}$ $yr^{-1}$ | ROM 400 kg N $ha^{-1}yr^{-1}$ |

The treatments were laid out according to a randomized complete block design (RCBD) (Figure 3.3), with the actual treatments shown in Table 3.3.

| COMMERCIAL TEA | ROAD | Replicate 1 | Replicate 2 | Replicate 3 | GUARD ROW | ROAD |
|---|---|---|---|---|---|---|
| | | GUARD ROW | | | | |
| | | Treatment 2 | Treatment 7 | Treatment 5 | | |
| | | Treatment 6 | Treatment 1 | Treatment 7 | | |
| | | Treatment 4 | Treatment 3 | Treatment 4 | | |
| | | Treatment 3 | Treatment 4 | Treatment 2 | | |
| | | Treatment 1 | Treatment 2 | Treatment 3 | | |
| | | Treatment 5 | Treatment 5 | Treatment 6 | | |
| | | Treatment 7 | Treatment 6 | Treatment 1 | | |
| | | GUARD ROW | | | | |

**Figure 3. 3 Layout of treatments plots at Tingamira estate**

Plot size was 1.2 m × 2 (double rows) x 6, with a spacing of 1.2 m between rows and 0.75 m within rows (Figure 3.4). Row orientation was from West to East. Best management practices were applied to the experimental block in terms of weeding, fertilization and irrigation. A three year pruning cycle was followed with the first prune in June 2010 and the final pruning in June 2013, when the tea in the trial block was pruned to a height of 0.45 m from the ground. Tipping, a harvesting operation to create an even plucking table, whilst at the same time leaving some maintenance foliage, was performed at 0.55 m from the ground or at 0.10 m above the pruning height, on 20 October 2010, after the tea had recovered from pruning. Three tippings were done at this time to create an even plucking table before the normal harvesting started. When actual harvesting started the height of cutter bar on the ROM was set at 0.60 m from the ground, the last tipping height, and subsequent height adjustments were based on this height, with the cutter bar being raised by 1 cm after every three plucking rounds throughout the study period.


**Figure 3. 4 Mechanical harvesting trial, showing plot layout.**

### 3.3 Weather data

Weather data was collected from an automatic weather station (Figure 3.5) located 500 m from the study site. The automatic weather station consisted of an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, CS215-L relative humidity and temperature sensor (Campbell Scientific Inc., Utah, USA) installed in a gill screen, a cup anemometer to measure wind speed (R.M. Young, Minnesota, USA) and a Pronamic Professional rain gauge Model TR-525M-R2 (Pronamic Co. Ltd Silkeborg, Denmark), which were all connected to a CR216X data-logger (Campbell Scientific Inc., Utah, USA). Mean temperature, as well as monthly cumulative precipitation, of the study site for the 2010/2011 to 2012/2013 growing seasons were recorded (Table 3.4).

**Figure 3.5 Campbell Scientific Automatic weather station installed at the study site for the period 2010-2013**

**Table 3.4 Mean temperature and total rainfall recorded during the 2010 to 2013 growing seasons, Tingamira estate, Chipinge, Zimbabwe**

| Year | Variable | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2010 | **Temp$_{\textbf{(mean)}}$**(°C) | 24.1 | 23.8 | 24.9 | 22.0 | 21.0 | 23.0 | 24.0 | 23.2 | 23.4 | 22.4 | 23.7 | 23.6 |
| | **Rain (mm)** | 172.0 | 497.0 | 108.0 | 168.0 | 126.0 | 13.0 | 28.0 | 2.0 | 39.0 | 8.0 | 185.0 | 211.0 |
| 2011 | **Temp$_{\textbf{(mean)}}$**(°C) | 23.0 | 21.9 | 22.3 | 21.1 | 17.2 | 15.4 | 16.0 | 15.3 | 18.6 | 22.8 | 22.1 | 23.0 |
| | **Rain (mm)** | 498.0 | 85.0 | 48.0 | 202.0 | 0.0 | 0.0 | 4.0 | 1.5 | 3.8 | 32.8 | 139.0 | 283.0 |
| 2012 | **Temp$_{\textbf{(mean)}}$**(°C) | 24.5 | 28.4 | 20.4 | 17.3 | 15.0 | 14.9 | 13.6 | 17.1 | 19.4 | 20.3 | 20.6 | 21.1 |
| | **Rain (mm)** | 135.0 | 94.0 | 106.2 | 78.0 | 3.4 | 2.6 | 0.2 | 0.4 | 44.2 | 31.4 | 88.2 | 117.0 |
| 2013 | **Temp$_{\textbf{(mean)}}$**(°C) | 21.3 | 20.8 | 19.8 | 17.4 | 15.3 | 15.8 | 14.0 | 16.9 | 19.6 | 21.6 | 22.4 | 23.5 |
| | **Rain (mm)** | 490.8 | 153.6 | 94.4 | 47.0 | 17.6 | 7.0 | 13.4 | 9.2 | 66.4 | 39.0 | 98.0 | 142.0 |

### 3.4 Yield determination

The green leaf yield from the individual plots was recorded at each harvest by weighing the green leaf (GL) harvested from each plot with a Camry scale (25 kg × 100 g) (Figure 3.6). The plot yields were obtained monthly for a period of one year and reported as total GL yield in kg $ha^{-1}$ $yr^{-1}$. This was done over a three year pruning cycle.

**Figure 3. 6 Green leaf yield weighing and recording at the study site, Tingamira estate, Chipinge, Zimbabwe**

### 3.5 Yield component determination

A 100 g shoot sample was randomly collected from each treatment per plot in each replicate after each harvest for the determination of percentage green leaf quality, shoot composition and shoot mass.

#### 3.5.1 Green leaf quality determination

The % good leaf was determined by classifying the harvested green leaf into different categories of immature leaf, good leaf (that included good whole leaf, two leaves and a bud, three leaves and a bud, soft banjhi, soft loose leaf and good cut leaf) and bad leaf (anything not included in good leaf) (Figure 3.7), expressed as a percentage by mass of the 100 g sample.

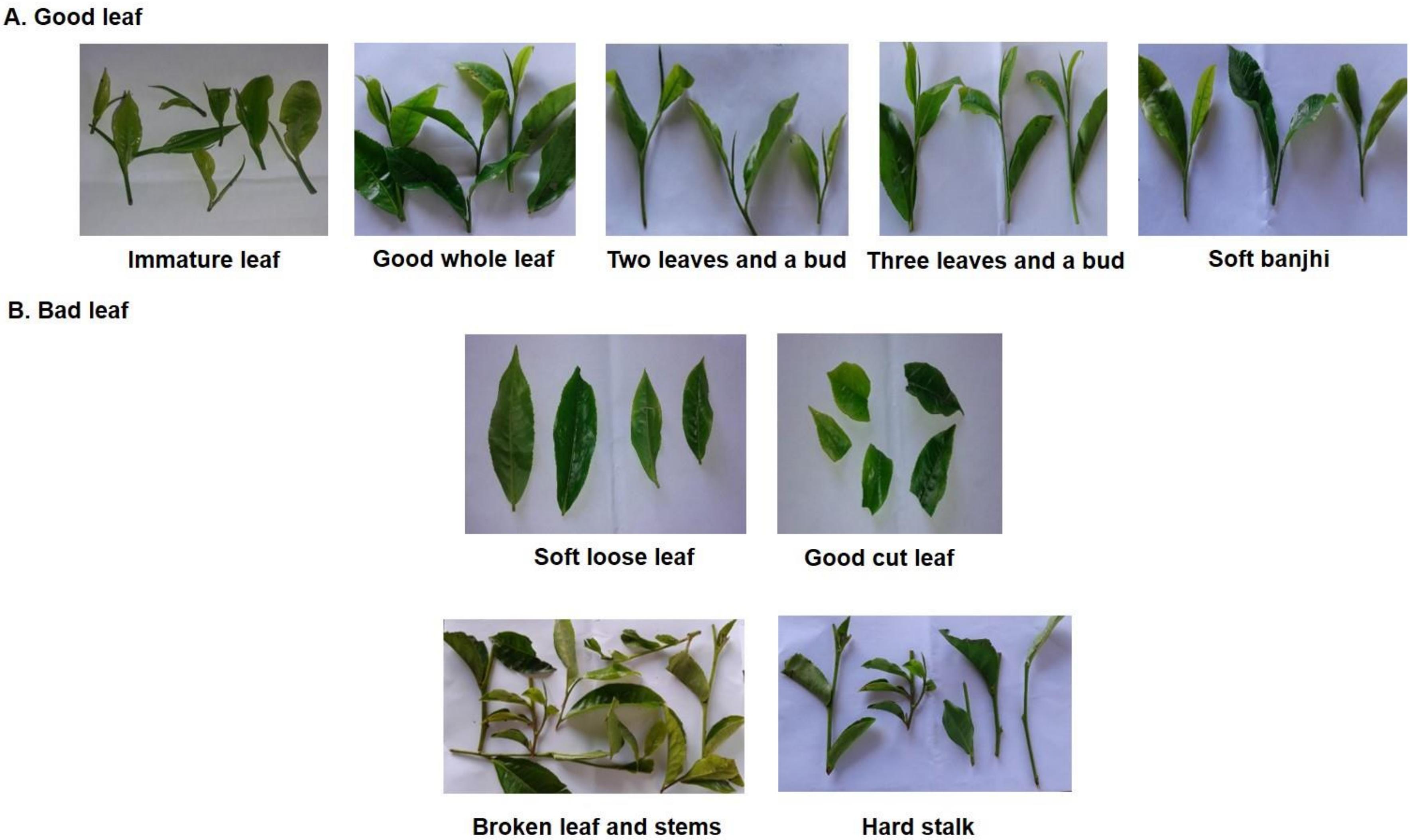


**Figure 3. 7 Different shoot component grades which make up A) good leaf and B) bad leaf**

### 3.5.2 Shoot composition determination

The sample collected at each harvest was separated into the different shoot components, viz.,buds (B), one leaf and a bud (1 + b), two leaves and a bud (2 + b), three leaves and a bud (3 + b), four leaves and bud (4 + b), whole loose leaf (WLlf), soft banjhi (SB), hard banjhi (HB), half cut leaf (½Clf), three quarter cut leaf (¾Clf) and broken pieces of stems and leaves (BPSlf). A banjhi shoot is a dormant shoot that is recognized by a small terminal bud, usually not more than 2–3 mm in length. The separated shoot components were then weighed and their mass expressed as a percentage of the total 100 g sample.

### 3.5.3 Shoot density determination

Shoot density was determined by using a 1 $m^2$ quadrant which was randomly thrown on individual bushes in their respective plots three times before each plucking. To maintain consistency the randomly selected bushes were marked and shoot density sampling was done from the same marked bushes for the entire three year study period. Actively growing shoots, consisting of buds, 1 + b, 2 + b, 3 + b and 4 + b, captured within the grid were counted and recorded as numbers of shoots $m^{-2}$ (Wachira, 1994)(Figure 3.8).

**Figure 3. 8 Shoot density determination using a 1$m^2$ quadrant at Tingamira estate**

### 3.6 Statistical analysis.

Analysis of variance (ANOVA) on yield and yield components, FI-PAR, rate of photosynthesis, black tea quality parameters, foliar, soil and nitrate N analysis and generation of graphs was performed for a factorial and added control experiment in a randomized complete block design using Genstat 14th edition computer statistical package (Payne, *et al.*, 2011), with the probability limit set at $p<0.05$. Mean separation for significant differences was done using the least significant difference (LSD) method. Duncan's Multiple Range Test (DMRT) was used to rank the means. Sigma plot 8.0 was used to generate graphs.

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# CHAPTER 4 [1]

# Yield decline in mechanically harvested clonal tea (*Camellia sinensis* (L) O. Kuntze) as influenced by changes in source/sink and radiation interception dynamics in the canopy

## 4.1 Introduction

Harvesting is an expensive operation in tea production, accounting for approximately 30 to 40% of the field management costs and 70% of the total labour force deployed on a tea estate (Goldsmith and Kilgour, 1999). Tea industries in central and southern Africa (Malawi, Mozambique, South Africa, Zambia and Zimbabwe) largely rely on manual labour for harvesting of tea. However, shortage of manual pluckers has affected tea cultivation in the region from the early 1990s. The extent of the labour problem has varied between countries and among estates within tea producing areas. For instance, farmers along the eastern border of Zimbabwe have been severely affected by the labour shortages due to the low minimum wage and industrial unrest (Masasa, 1999).

The ever increasing labour shortages meant that mechanical harvesting became a necessity, however, it is problematic as yields tend to decline as a result of mechanical harvesting. Studies performed in Malawi and Zimbabwe (Madamombe, 2008) showed that the different mechanical harvesting methods negatively impact growth parameters, such as shoot size, density, composition and mass and ultimately harvesting only 42-day old shoots is difficult due to overlapping shoot generations (Nyirenda, 2001), thus leading to shoots being harvested before they reach an optimum size. In contrast, under hand plucking, most of the immature shoots are left behind during harvesting and the maintenance foliage constantly provides photo-assimilates for the growing new shoots (Manivel and Hussain, 1982a). Maintenance foliage consists of permanent leaves retained in the frame of a pruned and plucked tea bush, which nourishes the pluckable young shoots providing photo-assimilates for respiration and growth (Manivel and Hussain, 1982a). Under hand plucking the maintenance foliage (source leaves) is

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deliberately left and allowed to accumulate below the plucking table to ensure continued production of photo-assimilates for new shoot growth (sinks). Mechanical harvesting therefore influences the way shoots are removed from the bushes with shoots of different generations being removed at the same time. An understanding of these dynamics within mechanically harvested tea bushes could provide insight into causes of the yield decline and possible mitigating treatments to limit the decline.

Dry matter production is central to the productivity of any crop and this depends on net accumulation of photo-assimilates. In tea, the low yields associated with mechanical harvesting are believed to be compounded by the fact that tea has inherently low productivity (500 – 2500 kg $ha^{-1}$ $year^{-1}$ of harvested plucked young shoots), which can be partly attributed to harvesting removing much of the active productive leaf area and nutrients (Mohotti and Lawlor, 2002). This is further compounded by inadequate assimilate production (source limitation), as the rates of photosynthesis are low (2-14 µmol $m^{-2}$ $s^{-1}$) compared to most other C3 plants (Mohotti*, et al.*, 2000, Mohotti and Lawlor, 2002, De Costa*, et al.*, 2007). According to Manivel & Hussain (1982b), plucking results in considerable depletion of dry matter produced by the maintenance leaves in the canopy. In addition, as tea is thought to have originated as an understory plant in tropical rainforests, it is likely that the photosynthetic apparatus is adapted to function optimally under shade (De Costa*, et al.*, 2007) and photosynthesis may be reduced under high light intensities as a result of photoinhibition (Mohotti and Lawlor, 2002).

Tea yields may also be sink-limited due to the continual removal of shoots (sinks) before they obtain a maximum biomass, which is required to maintain quality characters of made tea (De Costa*, et al.*, 2007). Tea bushes may therefore have an inadequate number of growing shoots to use photo-assimilates produced by photosynthesis (Squire, 1977, Tanton, 1979, Mohotti and Lawlor, 2002). This situation is likely to be exacerbated under continuous mechanical harvesting, where removal of shoots is indiscriminate of age and often the strongest sinks are removed, which are the single buds and single leaf and a bud (Manivel and Hussain 1986). In some cases, where the harvested material is both source and sink e.g. grass swards, the partitioning of photo-assimilates is crucial, as successful regrowth after cutting depends upon the mobilization of photo-assimilates to regenerate the new canopy (Porter and Hay, 2006). According to DeJong (1999) dry matter partitioning is the net result of the availability of resources to be partitioned, the conditional growth capacity and maintenance respiration requirements of the organ and the relative ability of the organ to compete with available resources.

It was therefore hypothesised that the decline in yield as a result of mechanical harvesting in tea is a result of the indiscriminate removal of foliage from the plucking table which leads to a change in the PAR interception dynamics and sink/source relationships within the canopy. A plucking table is the height above the pruning mark where plucking is done. As a result whole plant photosynthesis is impacted, which ultimately impacts tea bush productivity. This study evaluated three harvesting methods, i.e. hand plucking, hand-held machines and ride-on machines, with the aim of determining how continuous mechanical harvesting influences PAR interception by the canopy, light-saturated photosynthetic rates within the canopy and shoot composition and dry mass of the harvested shoots.

## 4.2 Materials and Methods

### 4.2.1 Study site description

A full description of the study site is in Chapter 3 section 3.1

### 4.2.2 Experimental design

The experiment consisted of three harvesting methods (hand plucking (HP), where harvesting was done after every 10/11 days, hand-held machine (HHM) and ride-on machine (ROM), where harvesting was done after every 14 days) replicated three times. Fertilizer was maintained at 265 kg N $ha^{-1}$ $yr^{-1}$ on all treatments for the three year duration of the trial period. The full experimental design is described in Chapter 3 section 3.2

### 4.2.3 Yield determination

The green leaf yield per plot was recorded at each harvest by weighing the green leaf (GL) harvested from each plot with a Camry scale (25 kg x 100 g) and reported as total GL yield in kg $ha^{-1}$. The totals for each treatment in each replicate were recorded as annual yield over three seasons (2010/2011, 2011/2012 and 2012/2013 seasons) and reported as annual total GL yield in kg $ha^{-1}$. A season runs from June of the current year to July of the following year.

### 4.2.4 Shoot composition, shoot density and shoot mass determination

Methodology for shoot composition and shoot density is given in Chapter 3 section 3.5.2 and 3.5.3. Shoot fresh and dry mass was determined by separating the 100 g sample into 2+b and 3+b shoots. The different shoot components were then weighed to determine fresh mass; following which the samples were oven dried at 65ºC for 48 hours (or to constant mass). Data on shoot dry mass is expressed as average shoot mass for each category of shoots for each harvesting method.

### 4.2.5 Photosynthetically active radiation measurements

Fractional interception of photosynthetically active radiation (FI-PAR) was determined using an AccuPAR LP-80 Ceptometer (Decagon Devices, Inc, Pulman, Washington, USA). Measurements were taken immediately after harvesting (0 day), and then 5 and 10 days after harvesting on each plot at midday and preferably on cloudless days. Measurements were done on three bushes, which were randomly selected and tagged at the start of the trial in each plot to ensure consistency in data collection. Measurements were made above the canopy and at three levels in the tea bush: at 10 cm, 20 cm and 60 cm below the canopy surface. FI-PAR was determined at 10 cm below the plucking table by dividing the reading taken at this depth by the full sun reading and subtracting from 1 to give the proportion of PAR intercepted by the top 10 cm of the canopy. Fi-PAR at 20 cm was determined by subtracting the reading at 20 cm from the measurement at 10 cm, dividing by the full sun reading and subtracting from 1. This gave the proportion of PAR intercepted by the canopy from 10 to 20 cm below the canopy. Finally, the FI-PAR at 60 cm was determined by subtracting the reading at 60 cm from the measurement at 20 cm, dividing by the full sun reading and subtracting from 1. This gave the proportion of PAR intercepted by the canopy from 20 to 60 cm below the canopy. The values for each treatment in each replicate were averaged over the three seasons (2010/2011, 2011/2012 and 2012/2013 seasons) and reported as mean FI-PAR.

#### 4.2.6 Photosynthesis measurements

Photosynthesis (*A*) was measured using a LI-6400 XT photosynthesis system (Li-COR, Lincoln, Nebraska, USA). PAR in the chamber was set at a saturating light intensity of 1000 µmol $m^{-2}$ $s^{-1}$ (Smith*, et al.*, 1993, 1994, De Costa*, et al.*, 2007, 2009, Lin*, et al.*, 2014), humidity was maintained above 50%, to avoid stomatal closure, and leaf temperature was maintained between 28 and 30°C. The $CO_2$ concentration was adjusted to 400 µmol $CO_2$ $mol^{-1}$ with a $CO_2$ mixer and the air flow was kept constant at 500 µmol $s^{-1}$. The same tagged positions for measuring PAR interception were used for photosynthesis measurements. Measurements were performed between 08h00 and 14h00 from December 2012 to January 2013 on five healthy, recently matured leaves from three positions within the bush canopy, viz. at 10 cm, 20 cm and 60 cm below the surface. Thus a total of 15 leaves were measured for each rep of each treatment. Measurements were performed soon after plucking (0 day), and then 5 and 10 days after plucking at each marked position.

### 4.3 Statistical analysis

Analysis of variance (ANOVA) on yield, shoot density, and composition, shoot mass, root starch, FI-PAR, rate of photosynthesis and generation of graphs was performed for a factorial and added control experiment in a randomized complete block design using Genstat 14th edition computer statistical package (Payne et al., 2011). Separation of means was performed using Duncan's multiple range test (DMRT) at $p<0.05$.

### 4.4 Results

#### 4.4.1 Yield

In the 2010/2011 season there were significant differences in total monthly GL yield between HP and machine plucking treatments (HHM and ROM) ($p<0.001$) (Figure 4.1A). A general decline in yield was observed over the season under all the harvesting treatments, with HP consistently producing higher yields than machine plucking treatments, except in March 2011 when plots harvested with the HHM produced higher yields (3515 kg GL $ha^{-1}$) than either HP (2924 kg GL $ha^{-1}$) or ROM (2733 kg GL $ha^{-1}$). Lower yields were recorded under machine harvesting treatments in January 2011 as compared to hand plucked bushes, with yields increasing in March 2011 under the HHM. A decline in yield followed in April and May 2011 (Figure 4.1A), with the lowest yields recorded in May under all treatments.

During the 2011/2012 season harvesting started three months later than usual due to unfavourable conditions for shoot growth. Depending on temperature and rainfall harvesting normally begins in July for each season. The first yield was recorded in October with the highest GL yields (3282 kg $ha^{-1}$) found in the hand plucked bushes (Figure 4.1B). Yields in all treatments increased in December as a result of favourable temperatures and adequate moisture availability for shoot growth, and then decreased until the end of the season. There were significant differences in yield between treatments in six of the seven harvests ($p<0.05$) (Figure 4.1B), with the highest yields recorded in the HP treatments in four of the seven months. Significantly higher yields in the plots harvested with HHM as compared to HP were found in December and February, whilst in December harvesting with the ROM resulted in higher yields than HP.

As in the previous season, harvesting during the 2012/2013 season started five months late in December 2012 with HP producing the highest GL yields (2876 kg $ha^{-1}$) compared to the mechanical harvesting treatments. There were significant differences in yield between HP and machine harvesting treatment at five of the six harvests (Figure 4.1C). Hand plucked bushed achieved the highest yield in three of the six months compared with HHM and the ROM, whilst in January 2013 yields were highest in mechanically harvested plots as compared to HP. Yield increased under machine harvesting from December 2012 to February 2013 (Figure 4.1C) compared to HP, which exhibited more consistent yields at this time. A decline in yield was observed in all treatments from March 2013 onwards. Hand plucking produced the lowest yield in May compared to mechanical harvesting treatments.

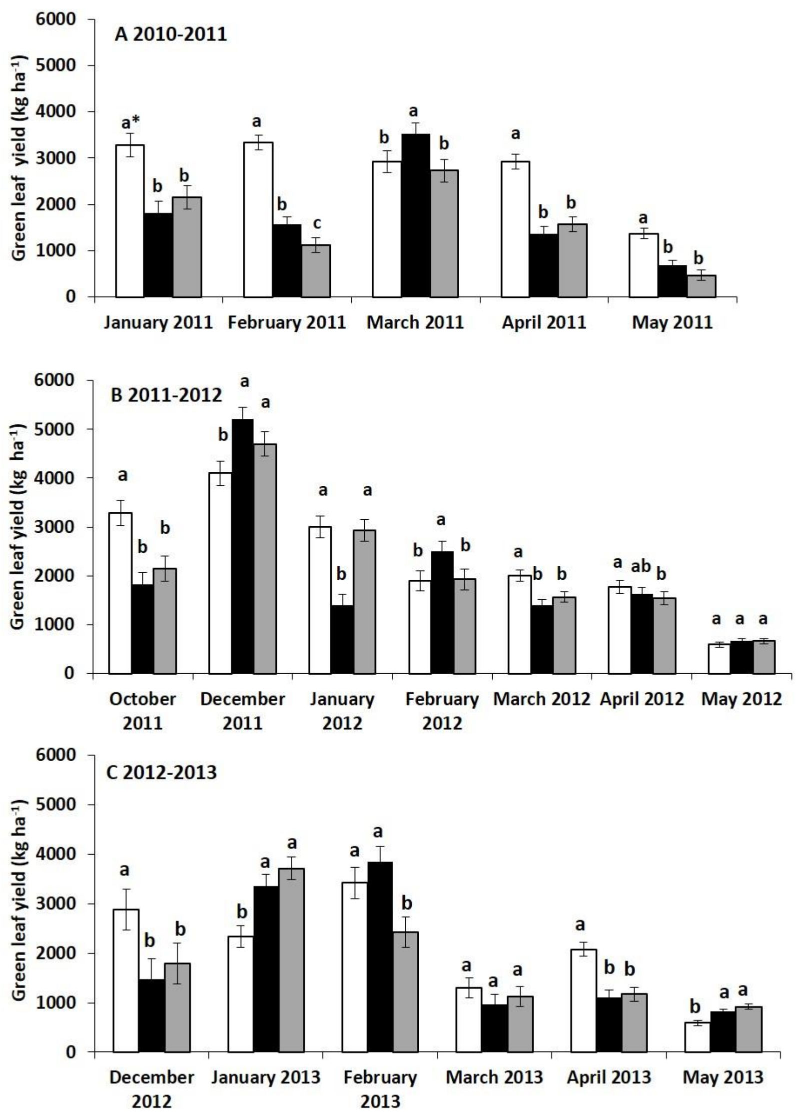


**Figure 4. 1 Total monthly green leaf yield of PC 108 at Tingamira Estate under hand plucking ( ),hand-held machine ( ) and ride-on machine ( ) in the A) 2010/2011 season, B) 2011/2012 season and C) 2012/2013 season (kg GL ha$^{-1}$).**

*** Means followed by the same letter within each month are not significantly different from each other at *p*<0.05 Duncan's Multiple Range Test**

All harvesting methods showed an increase in total seasonal GL yield from 2010/2011 to 2011/2012 seasons, with a decline in the 2012/2013 season (Table 4.1). Total seasonal GL yield was significantly higher in hand plucked bushes in the 2010/2011 season than the machine harvested treatments, but was only significantly higher than the HHM treatments in the 2011/12 and 2012/13 seasons ($p<0.05$). Over the three year pruning cycle significantly higher yields were realized in the hand plucked treatments as compared to both mechanically harvested treatments (Table 4.1).

**Table 4. 1 Total cumulative seasonal green leaf yield (kg GL $ha^{-1}$) of tea cultivar PC 108 at Tingamira estate from the 2010/2011 to 2012/2013 seasons**

| Method of harvesting | Harvesting seasons (kg GL $ha^{-1}$) | | | Total over seasons (kg GL $ha^{-1}$) |
|---|---|---|---|---|
| | 2010/2011 | 2011/2012 | 2012/2013 | |
| **Hand plucking** | 13 826 **a** | 16 643 **a** | 13 476 **a** | 43 945 **a*** |
| **Hand-held machine** | 8 965 **b** | 14 596 **b** | 11 553 **b** | 35 114 **b** |
| **Ride-on machine** | 8 029 **b** | 15 470 **ab** | 12 769 **ab** | 36 268 **b** |
| **LSD (0.05)** | **1796.4** | **1882.9** | **1455.1** | **4123.1** |
| **CV (%)** | **13.4** | **8.5** | **8.1** | **7.7** |
| **SED** | **824.5** | **864.2** | **667.8** | **1892.3** |

*** Means followed by the same letter in the same column are not significantly different from each other at p<0.05 Duncan's Multiple Range Test**

### 4.4.2 Shoot composition of harvested material

There were significant differences between harvesting methods in terms of % shoot composition of buds, 2+b, 3+b, 4+b, soft banjhi, hard banjhi, whole loose leaf, three quarter cut leaf, and broken pieces of leaf and stem ($p<0.05$) (Table 4.2). HHM and ROM resulted in a significantly greater number of immature shoots being harvested compared with HP, which included single buds and 1+bud, whilst a greater percentage of mature shoots (2+b and 3+b) were harvested under HP. Hard banjhi shoots were significantly higher under HP compared with machine harvesting treatments. As expected a higher percentage of cut leaf and broken pieces of stem and leaf were recorded using machine harvesting methods as compared to HP. The greatest number of 4+b shoots were recorded in ROM treatments than either HP or HHM.

**Table 4. 2 Mean shoot composition of harvested PC 108 material from the 2010/2011 to 2012/2013 seasons (% shoot composition by mass)**

| | Buds | 1+ b | 2+b | 3+b | 4+b | SB | HB | WLlf | ½Clf | ¾ Clf | BPSLf |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **HP** | 1.8 **b**[#] | 4.7 **a** | 26.4 **a** | 20.2 **a** | 4.6 **a** | 4.0 **a** | 8.8 **a** | 6.2 **a** | 0.0 **b** | 0.0 **c** | 23.3 **b** |
| **HHM** | 4.1 **a** | 5.3 **a** | 15.9 **c** | 12.1 **c** | 3.2 **b** | 2.8 **b** | 5.0 **b** | 5.1 **b** | 7.6 **a** | 8.1 **b** | 30.7 **a** |
| **ROM** | 2.3 **b** | 5.1 **a** | 18.2 **b** | 15.2 **b** | 4.8 **a** | 3.2 **b** | 5.4 **b** | 6.5 **a** | 7.9 **a** | 8.6 **a** | 22.8 **b** |
| **LSD** | **0.6**** | **NS** | **0.9**** | **0.7**** | **0.4**** | **0.4*** | **0.6**** | **1.2*** | **0.6**** | **0.4*** | **1.3**** |
| **CV** | **14.5** | **7.7** | **3.4** | **4.1** | **6.7** | **8.3** | **8.1** | **14.1** | **6.9** | **4.1** | **3.5** |
| **SED** | **0.3** | **0.3** | **0.4** | **0.4** | **0.2** | **0.2** | **0.3** | **0.5** | **0.3** | **0.2** | **0.6** |

**HP= hand plucking, HHM= hand-held machine and ROM= ride-on machine.**

**SB = soft banjhi, HB = hard banjhi, WLlf = whole loose leaf, ½Clf = half cut leaf, ¾Clf = three quarter cut leaf and BPSLf = Broken pieces of stem and leaf.**

**[#] Means followed by the same letter in each column are not significantly different from each other at p<0.05 Duncan's Multiple Range Test**

**NS = not significant.**

***$p<0.05$.**

****$p<0.001$.**

### 4.4.3 Shoot density

Harvesting method also had a significant impact on the number of harvested shoots in the different shoot classes, with the ROM harvesting more buds than HHM and HP ($p<0.05$)(Figure 4.2). Although, the lowest number of buds were harvested from HP bushes, it did not differ significantly from the HHM. A significantly greater number of 1+b shoots were harvested from bushes using HHM compared to HP and ROM, which did not differ significantly. The opposite trend was observed for 2+b and 3+b where a significantly greater number of these shoots were harvested from hand plucked bushes as opposed to machine harvested bushes (Figure 4.2). Significantly ($p<0.05$) more 4+b were harvested with machines than hand plucked bushes. Harvesting method impacted total number of shoots (buds, 1+b, 2+b, 3+b and 4+b) on the bushes, with machine harvesting treatments having more shoots $m^{-2}$ both before and after plucking than hand plucking (Figure 4.3). Total shoot densities before or after plucking did not differ between machine harvested plots (Figure 4.3).

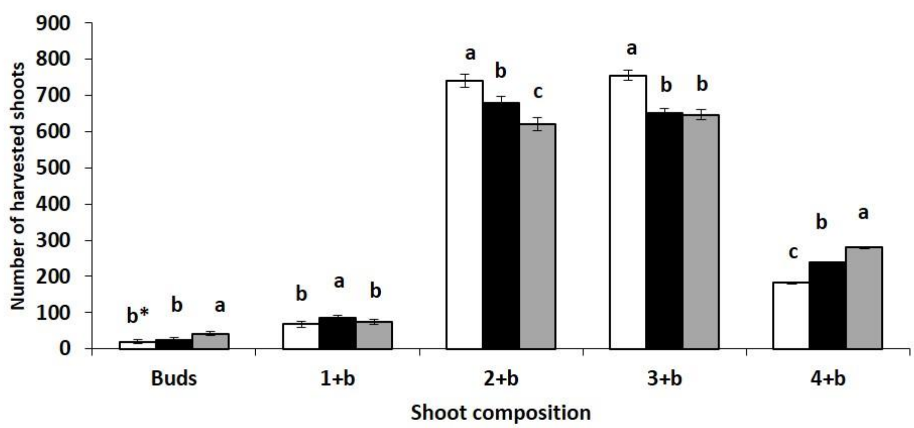


**Figure 4. 2 The effect of hand plucking ( ), hand-held machine ( ) and ride-on machine ( ) on shoot density on the PC108 tea bushes (totals over all harvests and seasons shoots $m^{-2}$)**

**[*] Means followed by the same letter at each shoot count are not significantly different from each other at $p<0.05$ Duncan's Multiple Range Test**

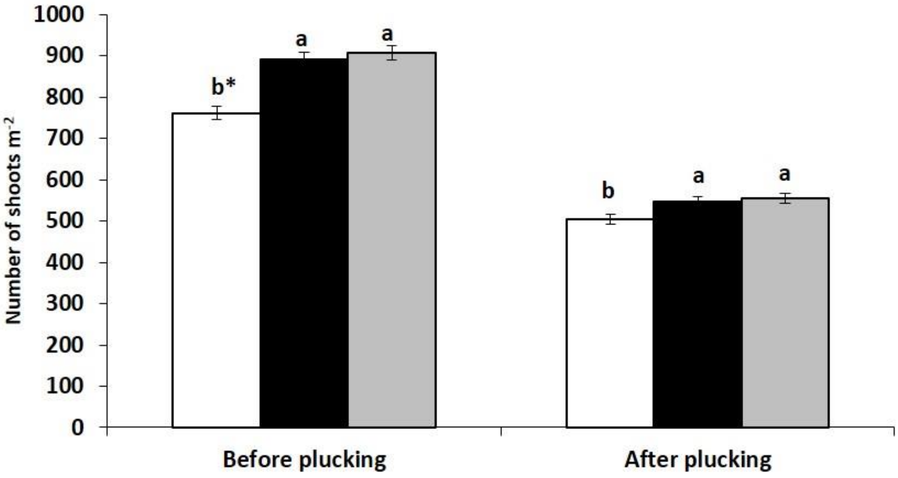


**Figure 4. 3 The effect of hand plucking ( ), hand-held machine ( ) and ride-on machine ( ) on total number of different shoot components before and after plucking on tea cultivar PC 108 (totals over all harvests and seasons)**

**[*] Means followed by the same letter within each shoot grouping are not significantly different from each other at *p*<0.05 Duncan's Multiple Range Test**

### 4.4.4 Shoot mass

There were significant differences between treatments in the average fresh and dry mass of 2+b and 3+b shoots at harvest over the three seasons ($p<0.05$) (Tables 4.3). Fresh and dry mass of 2+b shoots were significantly higher in the HP treatment than the mechanically harvested treatments in the 2010/2011 season, whilst only fresh mass of 3+b shoots was significantly higher in hand plucked bushes as compared to those harvested with HHM in this season. There were, however, no significant differences in either 2+b or 3+b shoot fresh or dry mass in the 2011/2012 season. In the 2012/2013 fresh mass of 3+b shoots under HP was significantly lower than either mechanically harvested treatment, whilst dry mass of 2+b shoots was significantly higher in HP treatments than ROM treatments. Across all seasons the dry mass of 2+b shoots in hand plucked bushes was significantly higher than mechanically harvested bushes, but there was no difference in the mass of 3+b shoots across all three seasons and harvesting methods.

**Table 4. 3 The mean mass (g) of 2+b and 3+b shoots of PC 108 at Tingamira estate from the 2010/2011 to 2012/2013 seasons**

| Harvesting method | 2010/2011 season | | 2011/2012 season | | 2012/2013 season | | Across all seasons | |
|---|---|---|---|---|---|---|---|---|
| | Fresh mass | Dry mass | Fresh mass | Dry mass | Fresh mass | Dry mass | Fresh mass | Dry mass |
| **2+b** | | | | | | | | |
| **HP** | 28.8**a**[#] | 5.8**a** | 25.6**a** | 4.7**a** | 22.8**a** | 5.7**a** | 25.4**a** | 5.3**a** |
| **HHM** | 23.6**b** | 4.6**b** | 22.8**a** | 4.3**a** | 24.3**a** | 4.9**ab** | 24.3**ab** | 4.5**b** |
| **ROM** | 24.3**b** | 4.8**b** | 23.2**a** | 4.4**a** | 22.4**a** | 4.6**b** | 23.3**b** | 4.6**b** |
| **LSD** | **4.37** | **0.9** | **NS** | **NS** | **NS** | **0.8** | **2.1** | **0.3** |
| **CV** | **12.2** | **13.3** | **9.5** | **9.5** | **9.4** | **11.2** | **6.1** | **7.7** |
| **SED** | **2.0** | **0.4** | **3.3** | **0.3** | **1.5** | **0.4** | **0.9** | **0.2** |
| **3+b** | | | | | | | | |
| **HP** | 35.3**a** | 6.2**a** | 27.2**a** | 5.4**a** | 25.0**b** | 5.9 **a** | 30.4**a** | 5.7**a** |
| **HHM** | 29.9**b** | 5.7**a** | 29.6**a** | 5.5**a** | 28.9**a** | 5.2 **a** | 29.0**a** | 5.5**a** |
| **ROM** | 32.2**ab** | 6.5**a** | 27.4**a** | 5.1**a** | 28.3**a** | 5.8 **a** | 29.0**a** | 5.7**a** |
| **LSD** | **3.7** | **NS** | **NS** | **NS** | **2.3** | **NS** | **NS** | **NS** |
| **CV** | **8.0** | **13.7** | **10.9** | **12.2** | **5.6** | **11.4** | **5.3** | **7.9** |
| **SED** | **1.7** | **0.6** | **2.1** | **0.4** | **1.0** | **0.4** | **1.0** | **0.3** |

**HP= hand plucking, HHM= hand-held machine and ROM= ride-on machine.**

**[#] Means within the same column followed by the same letter are not significantly different from each other at p<0.05 Duncan's Multiple Range Test**

**NS = not significant**

### 4.4.5 Fractional interception of photosynthetically active radiation (FI-PAR) following plucking

The fraction of PAR intercepted by the canopy was significantly affected by the level within the canopy at which measurements were made following shoot regrowth after plucking ($p$<0.05), with a decline in FI-PAR from the plucking table to 60 cm below the plucking table observed under all the different harvesting treatments (Figure 4.4). FI-PAR in the top 10 cm of the canopy also increased with time after plucking in all treatments, indicating shoot regrowth following harvesting. Significantly more PAR was intercepted in the top 10 cm of the canopy in the hand plucked bushes compared to the machine harvesting treatments soon after plucking, 5 days and 10 days after plucking. However, at 20 cm and 60 cm below the plucking table significantly more PAR was intercepted in the machine harvesting treatments compared to HP. Less than 4% of incoming PAR reached 60 cm below the plucking table in the HP treatment, whilst 10 days after plucking 12% of PAR reached 60 cm below the plucking table in the HHM harvested bushes and 15% in ROM harvested plots.

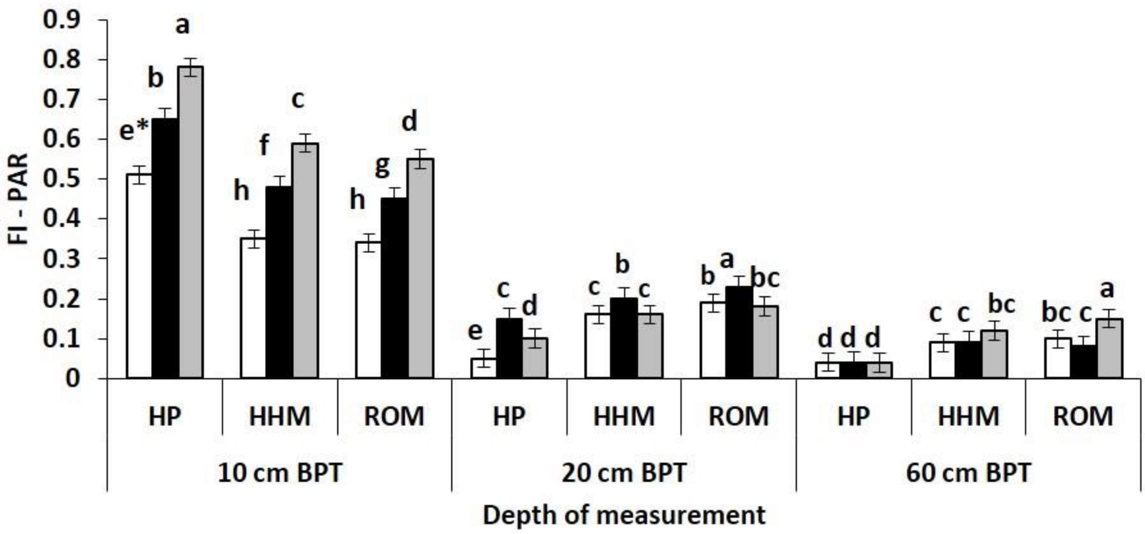


**Figure 4. 4 Mean FI-PAR dynamics within the tea bush canopy of PC 108 under different harvesting methods at 0 DAP ( ), 5 DAP ( ) and 10 DAP ( ). (DAP= days after plucking, BPT= below plucking table)**

*** Means within the same canopy depth under the different harvesting methods followed by the same letter are not significantly different from each other at p<0.05 Duncan's Multiple Range Test**

### 4.4.6 Photosynthesis

The light-saturated photosynthetic rate ($A_{max}$) of individual leaves differed significantly between the harvesting methods at the different measurement depths (10, 20 and 60 cm below the plucking table) and at the different measurement intervals (0, 5 and 10 days after plucking) ($p$<0.001) (Figure 4.5). Photosynthesis was highest in the top 10 cm and lowest at 60 cm below the plucking table for all treatments, reflecting PAR distribution throughout the tea bush. At 10 cm below the plucking table, $A_{max}$ was significantly higher in the hand plucked bushes than machine harvested bushes following shoot regrowth. Whilst an increase in $A_{max}$ at 10 cm below the plucking table was observed 5 and 10 days following plucking in hand plucked bushes and those harvested with ROM, a similar trend was not evident in bushes harvested with HHM, where there was no increase in $A_{max}$ between 5 and 10 days after plucking. Although there were significant differences between treatments at 20 cm below the plucking table, there was no consistent trend between treatments over time. Bushes under ROM had significantly higher $A_{max}$ at 60 cm as compared to hand plucked bushes at all three measurement intervals, whilst bushes harvested with HHM only showed significantly higher $A_{max}$ at 5 and 10 days after harvesting. The photosynthetic rate decreased over the shoot regrowth period under ROM at 60 cm below the plucking table, with the highest $A_{max}$ recorded at 0 days after plucking and lowest at 10 days after plucking.

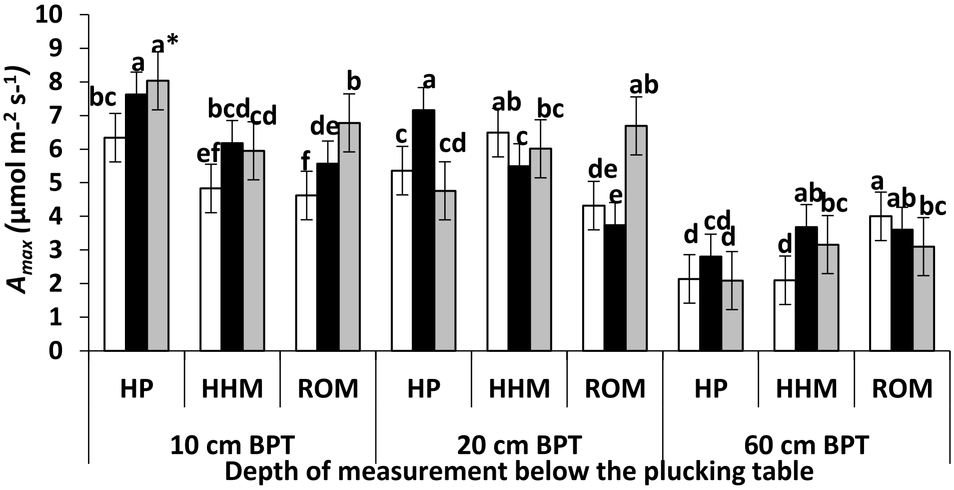


**Figure 4.5 Photosynthetic rate (*A*), under different harvesting methods at different depths below the plucking table, 0 DAP ( ), 5 DAP ( ) and 10 DAP ( ) (DAP= days after plucking, BPT= below plucking table)**

*** Means followed by the same letter within each canopy depth are not significantly different from each other at $p<0.05$ Duncan's Multiple Range Test**

### 4.5 Discussion

This study has confirmed results from previous studies (Wijeratne, 1999, Mukumbarezah, 2001, Nyasulu, 2006, Madamombe, 2008,) that mechanical harvesting reduces yield, with yield declining between 17 and 19% under continuous mechanical harvesting, as compared to hand plucking over the three year pruning cycle. As the implementation of mechanical harvesting is non-negotiable on many tea estates, it is critical that the underlying mechanisms causing the yield reduction are understood in order to try and implement mitigating actions that might limit the yield loss. The yield components of tea are the number of plucked shoots per unit area of land and the mean mass per shoot (Carr, 2010a, De Costa*, et al.*, 2007) and therefore mechanical harvesting must reduce either one or both of these parameters.

Mechanical harvesting has been reported to indiscriminately remove vegetation above the plucking table, which includes buds and immature (1+b) and overgrown shoots (4+b) (Mukumbarezah, 2001, Nyasulu, 2006, Mouli*, et al.*, 2007, Madamombe, 2008). Similar results were observed in this study, with hand plucking showing a higher percentage of 2+b and 3+b (46.6%) shoots making up total harvested shoot composition as compared to buds, 1+b and cut leaf (29.8%). However, in the mechanical harvesting treatments the reverse was true and buds, 1+b and cut leaf made up between 46 and 56% of the total shoots harvested. The most desirable shoots for plucking are the 2+b and 3+b shoots, as they represent the best compromise between yield and quality (De Costa*, et al.*, 2007) and in mechanically harvested treatments these shoots only comprised 30-35% of the total harvested yield. In addition, when comparing average mass of the shoots over the pruning cycle it is evident that dry mass of 2+b shoots was higher in hand plucked bushes than mechanically harvested bushes. The overall decline in yield observed in mechanically harvested tea was therefore a result of a combination of reduced number and dry mass of the most desirable shoots. This is in agreement with a study on yield decline over the pruning cycle in Sri Lanka, where the decline in yield was paralleled with changes in canopy leaf area index and mature leaf dry mass (De Costa*, et al.*, 2009).

The question therefore arises as to why there is a lower percentage of desirable shoots under mechanical harvesting. To explain this trend it is necessary to examine sink/source relationships and factors contributing to shoot initiation and growth and dry matter accumulation by the shoots. As these bushes were all grown under the same conditions it is unlikely that any environmental factor or water stress was responsible for the observed variation in yield and differences could only be attributable to the harvesting method. Tea yield depends on the renewal of shoots following harvesting through axillary bud break immediately below the plucked point and then the growth of these shoots using photo-assimilates provided by the maintenance foliage. According to De Costa*, et al.* (2007) the rate and duration of shoot initiation and expansion is dependent on a) initiation of shoots and leaves, b) extension of shoots and expansion of leaves, c) production of photo-assimilates and d) partitioning of photo-assimilates to shoots. In addition, the ability to harvest the most desirable shoots depends on the rate of shoot growth and the size of the shoot generations, where shoots at the same stage of growth are referred to as a generation (De Costa*, et al.*, 2007). Under regular short plucking intervals equal numbers of shoots are found in each generation, however, after pruning or after a long stress period (temperature or water availability) bud break is synchronized which gives rise to just one or two generations. The number of generations is also reduced under mechanical harvesting, which is attributed to the non-selectivity of harvesting (De Costa*, et al.*, 2007), as observed in the current study. The non-selective harvesting of shoots is also bound to be exacerbated on clonal tea, such as PC 108, with a more horizontal leaf pose (TRFCA, 2000). A small number of generations on a tea bush often means that the majority of a crop for a year will be harvested in a short period of time, which is evident in all three seasons during this study.

The increased number of buds and 1+b shoots harvested by the machines and remaining on the bushes after harvest indicates a greater percentage of immature shoots on these bushes, which is likely a result of the indiscriminate removal of material by the machine and an increase in axillary bud break. These young buds and 1+b shoots are reported to be the strongest sinks (Rahman, 1988) and therefore due to the proliferation of these shoots on mechanically harvested bushes there is likely to be increased competition for available resources from the maintenance layer. The first 10 cm below the plucking table consists of the maintenance foliage, which is responsible for the production of photo-assimilates needed to support the growth of new shoots (Manivel and Hussain, 1982a). Okano*, et al.* (1995) found that 85% of photosynthesis occurred in the top 5 cm of the canopy and maximum canopy depth for effective photosynthesis was 10 cm, whilst De Costa*, et al.* (2007) suggests that the top two layers (0-10 and 10-20 cm) contribute 80-90% of gross photosynthesis. Interception of PAR in this top 10 cm layer was significantly lower in mechanically harvested bushes in the present study as opposed to hand plucked bushes, indicating a depleted maintenance layer in mechanically harvested bushes with fewer leaves. Taken together with the lower light-saturated photosynthetic rates in this layer in mechanically harvested bushes, it is likely that production of photo-assimilates for shoot growth is compromised and these bushes are source limited. Burgess et al.

(2006) also suggests that when the leaf area index of tea bushes falls below a certain critical level (suggested to be 4 $m^2$ $m^{-2}$) the associated reduction in interception of solar radiation has a significant impact on yield and long term plant vigour. The rates at which new shoots are able to grow is therefore retarded as a result of increased competition for a smaller pool of available photo-assimilates. A consequence of this is the reduced percentage of desirable shoots on machine harvested bushes, which decreases as the season progresses. On the other hand, the selective nature of hand plucking leaves immature shoots (buds and 1+b) on the bushes, which are strong sinks and will continue to grow such that they will be plucked in the following plucking round. There is therefore more generations of shoots on these bushes which will facilitate more even yield when conditions for growth are favourable.

**4.6 Conclusions**

The indiscriminate removal of foliage by the machines altered canopy architecture, as compared to hand plucked bushes, resulting in a decrease in PAR interception in the top 10 cm of the canopy. This reflected a depleted maintenance layer which when linked to lower light-saturated photosynthetic rates equated to a less active maintenance layer in these bushes, with the implication that these bushes were source limited. Shoot growth was further compromised in these bushes due to the presence of larger numbers of immature shoots (buds and 1+b) which are strong sinks and resulted in increased competition between these shoots for an already depleted assimilate supply. As a result the growth of these shoots was retarded, resulting in fewer desirable shoots of lower mass during each season.

A closer examination of the seasonal yield trends revealed that it may be possible to attain higher yields under mechanically harvested treatments than hand plucking during the peak months of January, February and March, when conditions are favourable for shoot growth. As a compromise machine harvesting could be used in the main growing season and hand plucking during the lean periods in order to maximize the harvest of as much leaf as possible. It is, however, important that the machines are properly handled. This includes careful management of the height of machines to avoid cutting deep into the maintenance foliage which has a thinning effect. This will also ensure that all shoot generations are not removed all at once and some of the immature shoots will be left on the table, forming the basis for the following harvest. Using the method of monitoring harvesting intensity by Mouli*, et al.* (2007) may aid in determining appropriate machine heights to sustain yield throughout the season, a principle that has also been demonstrated by Rahman (1988). Management practices that promote growth of maintenance foliage should also be prioritised, such as proper fertilization and irrigation to avoid water stress. Finally, engineering solutions should be sought to design machines that mimic hand plucking by plucking shoots instead of cutting them, which will bring about an element of selectivity as only mature leaves are plucked, thereby allowing more shoot generations on a bush.

The hypothesis was accepted.

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# CHAPTER 5

# The impact of continuous mechanical harvesting of tea (*Camellia sinensis* (L) O. Kuntze) and increasing nitrogen application rate on black tea quality parameters.

## 5.1 Introduction

Black tea is one of the cheapest and most popular non-alcoholic stimulants consumed throughout the world and is manufactured from *Camellia sinensis* (L) O Kuntze, grown in tropical and temperate countries (Ravichandran and Parthiban, 1998, Maina and Kaluli, 2013). Young tender shoots of tea, consisting of two or three leaves and a bud, are harvested periodically to produce either black (i.e. withered and fermented), green (withered but unfermented) or oolong (withering and semi-fermented) tea (Wang*, et al.*, 2000, De Costa*, et al.*, 2007, Chen*, et al.*, 2015). The profitability of any tea operation is governed by the quantity and quality of the plucked shoots (Ravichandran and Parthiban, 1998, Maina and Kaluli, 2013). However, there has been concerns about a decline in both quantity and quality as results of mechanical harvesting of tea. Tea in central and southern Africa (Malawi, Mozambique, South Africa, Zambia and Zimbabwe) has traditionally been hand harvested without causing unnecessary injury to the plucked leaf; however, with the acute labour shortage and the ever increasing labour cost, mechanical harvesting had to be adopted.

In most tea production systems there is continual conflict between the requirements to harvest the maximum amount of leaf, whilst maintaining an acceptable plucking standard that is not detrimental to tea quality. The quest to find suitable mechanical methods, which are fast, cheap and can maintain a plucking standard that results in high yield and quality has generated much interest in the mechanical harvesting of tea (Kilgour and Brighton, 1999), resulting in the full mechanization of shoot harvesting by using hand-held machines and ride-on machines on some estates in central and southern Africa. Mechanical harvesting increases labour productivity and reduces the number of pluckers required to cover a given area (Ravichandran and Parthiban, 1998, Nandagopalan*, et al.*, 2014). However, with mechanical harvesting, the selectivity in plucking is lost and extensive mechanical injury is caused to the leaf harvested (Ravichandran and Parthiban, 1998, Nyasulu, 2006, Madamombe, 2008,). This is reasoned to lead to a deterioration in tea quality and hence price and profitability (Ravichandran and Parthiban, 1998).

Nutrition is one of the major factors that can be manipulated to influence the yield, if all other factors are non-limiting. Nitrogen is a critical element in tea production affecting yield and quality. Yields increase with increasing nitrogen application up to high levels (Sitienei*, et al.*, 2013). However, it is reported that a high quantity of nitrogenous fertilizers has a deleterious effect on quality of made tea, such that rates rarely exceed 300 kg N $ha^{-1}$ $yr^{-1}$ (Grice, 1990b, Venkatesan and Ganapathy, 2004) to maintain quality parameters.

This study was undertaken to determine how mechanical harvesting affects black tea quality parameters and whether it can be used successfully as an alternative to hand plucking. In addition, it also assessed how increasing the nitrogen application rate under continuous mechanical harvesting affects black tea quality parameters and tasters' evaluation, made tea density and fibre content. It was therefore hypothesized that 1) mechanical harvesting of tea can be used as an alternative to hand plucking as it does not reduces black tea quality in terms of tea tasters' valuation, made tea density, fibre content and biochemical compounds and 2) increasing the nitrogen application rate under mechanically harvested tea to increase yield will not lead to a reduction in the quality of good leaf and  black tea quality in terms of tea tasters' valuation, made tea density, fibre content and biochemical compounds.

## 5.2 Materials and methods

### 5.2.1 Study site description and experimental design

A full description of the study site, treatments and experimental design are provided in Chapter 3 sections 3.1 and 3.2.

### 5.2.2 Good leaf physical quality

The percentage green leaf was determined according to the method described in Chapter 3 section 3.5.1

### 5.2.3 Tea manufacturing

Manufactured black tea quality was only assessed in the third season, as this was the only season that access was granted to a mini tea manufacturing facility in Malawi. A sample weighing 300 g of green leaf plucked from each plot was collected in February (main growing period) and again in May 2013 (off - season) from the seven treatments and three replicates. The samples were subjected to normal wither and processed into black tea in a Tea Craft Mini Processing Unit (Tea Craft, UK) using the crush, tear and curl (CTC) method. The mass of the processed sample was subsequently recorded. Fibre extraction was performed by passing the sample through a Fibre Extraction machine (Tea Craft, UK) three times. This removes the fibre from the sample, leaving a clean sample. The cleaned sample was weighed, and its mass recorded. The cleaned sample of made tea was then used for the determination of made tea density, organoleptic assessments, Theaflavin and Thearubigin content and biochemical analyses.

### 5.2.4 Made tea density determination

Made tea density was determined using the free flow method. A 100 g sample of cleaned made tea was weighed and poured into a 250 $cm^3$ measuring cylinder and the volume of the sample determined (Jose, 2000). Density of the sample was then calculated using Eq. 5.1.

$$\textbf{Density} = \frac{\text{Volume of cleaned sample (cm3)}}{\text{Mass of cleaned sample (g)}} \quad \text{……... …………5.1}$$

Unlike the conventional equation for density (mass/volume), in the tea industry, density is equated as volume over mass (100 g in a standard test used) (Jose, 2000), which is the specific volume. Therefore, in this chapter the word density stands for the mean volume occupied by 100 g of made tea. According to Jose (2001b), using the term volumetrics means the larger the volume the lower the density, the smaller the volume the higher the density, with teas of higher densities being most desirable.

### 5.2.5 Black tea organoleptic assessment and valuation

Black tea organoleptic assessment and valuation was only done in the third year of the study (2013) after the initial pruning, in order to assess whether continuous mechanical harvesting had a long term effect on the valuation of black tea. Made tea samples of 20 g from each sample, from the seven treatments and three replicates, were sent for tasters' evaluation. Five grams of the sample were transferred to an infusion cup and boiling water added, covered and left to steep for five minutes. It was then filtered into an infusion bowl and the residue (infusion) was collected on the infusion cup lid. Both the liquor and infusion were then subjected to organoleptic evaluation (Kilel*, et al.*, 2013) by a panel of regular experienced tea tasters from Tea Brokers Central Africa (TBCA). The evaluation of the liquor was on a ten point scale for brightness, briskness, colour and strength (Wright, 2005). Sensory evaluation was made by two professional tea tasters, with expert knowledge of central and southern African tea, who scored the teas based on infused leaf colour, colour of liquor, strength and liquor quality to determine the parameters related to quality of made tea (Kottawa-Arachchi*, et al.*, 2012). Additional assessments were provided for the colour with milk and colour of the infusion. Total scores and valuation were also included in the assessments.

**5.2.6 Determination of Theaflavin and Thearubigin content in black tea samples**

The Flavognost method, as described by Hilton (1973), was used to determine the content of Theaflavins (TFs), whereas Thearubigins (TRs), brightness and total colour were determined using the method of Roberts and Smith (1963). Black tea extract (1 ml) was mixed with 1 ml isobutyl methyl ketone (IBMK) and the mixture was vortexed for 30 seconds four times. This avoids the formation of an emulsion. A sample from the aqueous bottom layer (185 µl) was mixed with 16 µl IBMK top layer and separated into solutions B and D (Figure 5.1). 32 µl IBMK layer (top layer) was mixed with 170 µl Methanol (solution A). The second top layer of IBMK (500 µl) was mixed with 500 µl of freshly prepared 2.5% aqueous $NaHCO_3$. The mixture was vortexed for 30 seconds and centrifuged for 5 minutes at 3500 rpm (Figure 5.1) to allow separation before discarding the lower layer. A portion of the IBMK top layer (32 µl) was mixed with 170 µl Methanol (solution C).

The extractions for each tea sample were done in duplicate. Solutions A, B, C, and D were prepared directly into ELIZA plates, adding the solution first then the sample. Shaking of the solution was done for 5 sec at medium speed in an ELIZA Reader and the absorbance $A_A$, $A_B$, $A_C$ and $A_D$ of solution A, B, C and D, respectively were read at 375 nm and 450 nm. TF and TR content in percentage were calculated using the following equations:

$$\%\ \text{Theaflavins at 375 nm} = E_c * 2.25 \quad \text{...a}$$

$$\%\ \text{Theaflavin at 450 nm} = E_c * 6.69 \quad \text{...b}$$

$$\% \text{ Thearubigins at 375 nm} = (2E_D + E_A - E_c) * 7.06 \text{ ......c}$$

$$\% \text{ Total Colour at 450 nm} = 6.25(E_A + 2E_B) \text{ ......d}$$

$$\% \text{ Brightness at 450 nm} = \frac{100*E_C}{E_A + 2E_C} \text{ ......e}$$

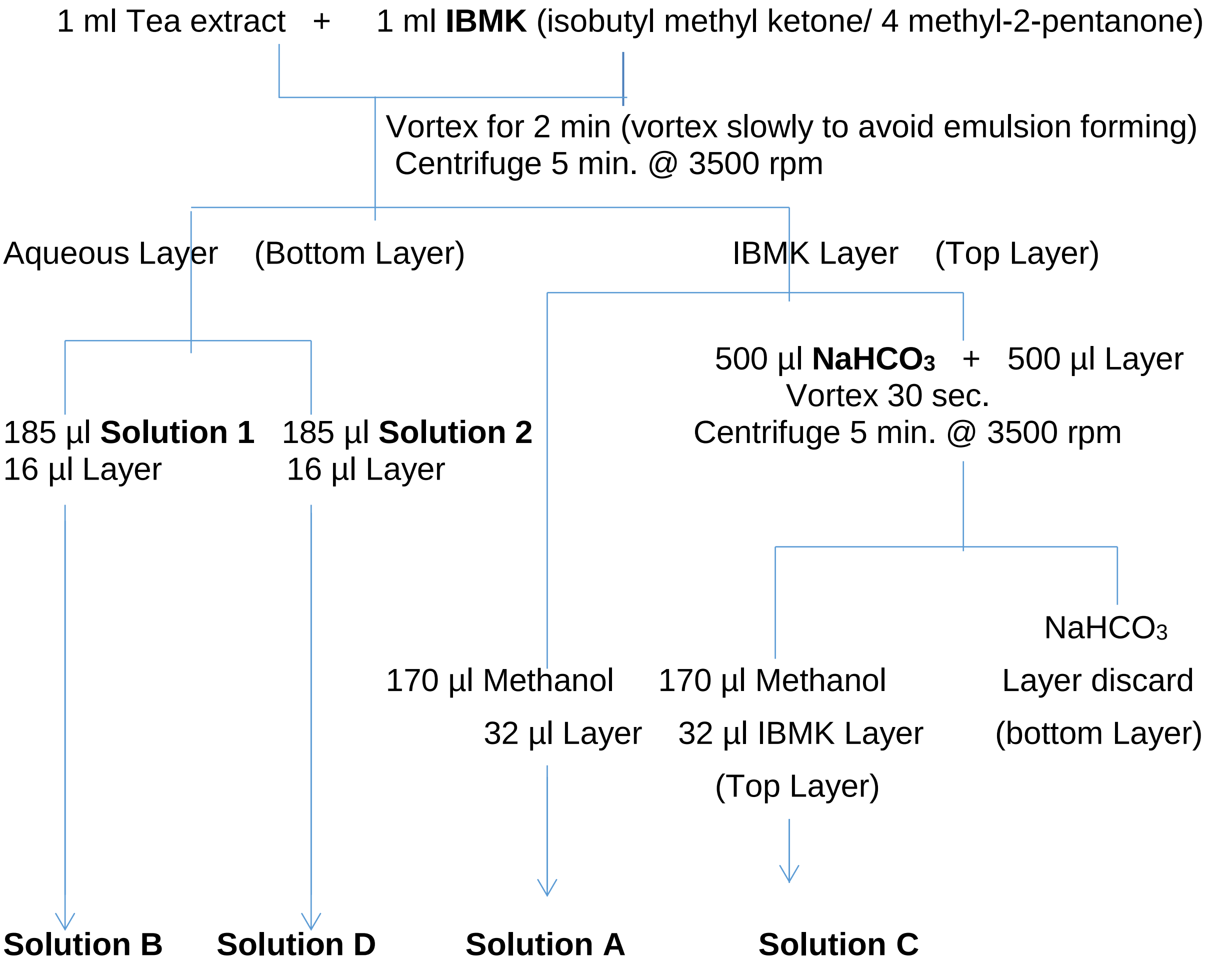


**Figure 5.1 Schematic diagram showing the extraction of Theaflavins and Thearubigins**

### 5.2.6 Determination of black tea quality parameters

All chemicals for UPLC-MS work were of ultra-pure LC-MS grade and purchased from Fluka (Steinheim, Germany), whilst ultra-pure solvents were purchased from Honeywell (Burdick & Jackson, Muskegon, USA). Ultra-pure water was generated from a Millipore Elix 5 RO system and Millipore Advantage Milli-Q system (Millipore SAS, Molsheim, France). The UPLC-MS analysis, as described by van der Westhuizen *et al.,* (2015) was used to determine the content of Theaflavins (TFs).

### 5.2.7 Instrumental

A Waters UPLC coupled in tandem to a Waters photodiode array (PDA) detector and a SYNAPT G1 HDMS mass spectrometer was used to generate accurate mass data. Chromatographic separation of the tea extracts was done utilising a Waters HSS T3 column (150 mm x 2.1 mm, 1.8 µm) and the temperature controlled at 60 °C. A binary solvent mixture was used consisting of water (Eluent A) containing 10 mM formic acid (natural pH of 2.3) and acetonitrile (Eluent B) containing 10 mM formic acid. The initial conditions were 100% A at a flow rate of 0.6 mL $min^{-1}$ with a linear gradient to 87% A at 31 minutes. The conditions were changed to 83% A at 33 minutes, 76% A at 37 minutes followed by another linear gradient change to 69% A at 41 minutes. The column was flushed with 100% B from 43 to 45 minutes and then changed to the initial conditions. The runtime was 50 minutes and the injection volume was 1 to 5 µl depending on the concentration of the compounds of interest. The PDA detector was scanned between 200 and 500 nm (1.2 nm resolution) and collecting 20 spectra per second.

The SYNAPT G1 mass spectrometer was used in V-optics and operated in electrospray mode to detect the compounds of interest. Leucine enkephalin (50 pg $mL^{-1}$) was used as reference calibrant to obtain typical mass accuracies between 1 and 3 m Dalton. The mass spectrometer was operated in positive and negative mode with a capillary voltage of 2.0 KV, the sampling cone at 30 V and the extraction cone at 5 V. The scan time was 0.1 seconds covering the 100 to 1000 Dalton mass range. The source temperature was 120 °C and the desolvation temperature was set at 450 °C. Nitrogen gas was used as the nebulisation gas at a flow rate of 800 L $h^{-1}$. The software used to control the hyphenated system and do all data manipulation was MassLynx 4.1 (SCN 704 Waters Corporation, Milford, MA). These analyses were performed at CSIR Biosciences by Prof. Steenkamp.

## 5.3 Results

### 5.3.1 Green leaf quality

Green leaf quality, measured as percentage of immature leaf, good whole loose leaf, two leaves and a bud, three leaves and a bud, soft banjhi, soft loose leaf and good cut leaf, was significantly higher ($p$<0.05) in hand plucked bushes (265 kg N $ha^{-1}$ $yr^{-1}$) than machine harvesting treatments at all fertilizer rates during the 2010/2011 and 2012/2013 seasons (Figure 5.2). In the 2010/2011 and 2011/2012 season % good leaf quality in plots harvested with HHM and ROM, with an N application rate of 265, 300 and 400 kg N ha$^{-1}$ yr$^{-1}$ were not significantly different to each other (p<0.05). In 2012/2013 season, a 2% increase in % green leaf quality under HHM was observed after increasing N-application rate from 265 to 400 kg N ha$^{-1}$ yr$^{-1}$, however no significant differences were observed between the 300 and 400 kg N ha$^{-1}$ yr$^{-1}$ application rates. There was a 3% increase in % green leaf quality in bushes harvested with ROM after increasing the N-application rate from 265 to 400 kg N ha$^{-1}$ yr$^{-1}$ in the same season, although the 265 and 300 kg N ha$^{-1}$ yr$^{-1}$ were not significantly different from each other (Figure 5.2). However, in the third season only bushes harvested with the ROM, with an N-application rate of 300 kg N ha$^{-1}$ yr$^{-1}$ exhibited significantly lower % good leaf quality than hand plucked bushes. This effect therefore probably has little to do with N application rate and was more likely a harvesting effect, whereby the third year bushes harvested with machines seemed to have recovered.

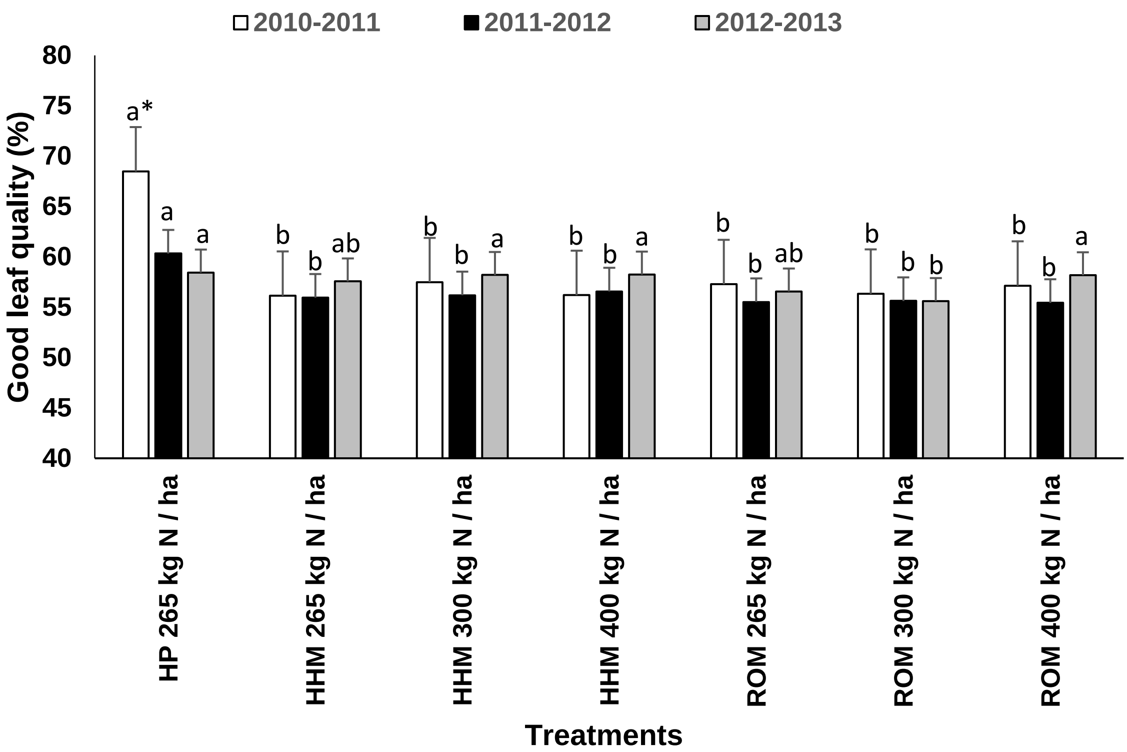


**Figure 5. 2 Effect of increasing N-application rate under harvesting methods on mean % good leaf quality during the 2010/2011 to 2012/2013 seasons**

***Significant at p<0.05,**
**[1]Means in each season, followed by the same letter, are not significantly different from each other at P<0.05, Duncan's Multiple Range Test (DMRT)**

### 5.3.2 Black tea quality

#### 5.3.2.1 Organoleptic assessment and valuation

Tea quality is defined by the appearance of dry tea, as well as the colour, aroma and taste of the tea liquor (Zheng*, et al.*, 2016). Liquor colour, liquor strength, briskness, brightness and colour of infusion showed no differences between hand plucking and machine harvesting treatments during the main growing period (February 2013) and off-season (May 2013) (Table 5.1). Generally higher scores were recorded in treatments which produced higher yields (HMM at all levels) and lower scores under treatments which recorded lower yields (ROM at all levels) although the scores between the harvesting techniques did not differ (Table 5.1). In May 2013, there was a general increase in tea tasters' score on liquor colour, strength, brightness and colour of infusion, compared with February 2013 assessment date. The relationship between high yield and high organoleptic score was also evident during this period of slow growth, although some variation was observed. Higher yields and a general increase in the scores for brightness and colour of infusion was observed when using ROM machine harvesting and increased fertilizer application at this time.

**Table 5. 1 Effect of harvesting method and increasing N-application rate on organoleptic assessment by Tea Brokers Central Africa (TBCA) in February 2013 and May 2013**

| Treatment | Liquor Colour | | Liquor Strength | | Briskness | | Brightness | | Colour of infusion | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Feb | May | Feb | May | Feb | May | Feb | May | Feb | May |
| HP 265 kg N $ha^{-1}$ | 3.9 | 4.3 | 4.2 | 4.3 | 3.2 | 2.3 | 2.3 | 4.0 | 4.2 | 4.7 |
| HHM 265 kg N $ha^{-1}$ | 4.1 | 4.3 | 3.6 | 4.0 | 1.5 | 2.3 | 3.5 | 3.3 | 3.6 | 5.0 |
| HHM 300 kg N $ha^{-1}$ | 4.0 | 3.7 | 4.3 | 4.0 | 2.9 | 1.7 | 2.0 | 2.7 | 4.3 | 4.3 |
| HHM 400 kg N $ha^{-1}$ | 4.0 | 4.0 | 4.3 | 4.3 | 3.0 | 2.7 | 2.0 | 3.3 | 4.3 | 4.3 |
| ROM 265 kg N $ha^{-1}$ | 3.7 | 4.0 | 4.0 | 4.0 | 2.3 | 2.3 | 1.3 | 3.7 | 3.7 | 4.7 |
| ROM 300 kg N $ha^{-1}$ | 3.7 | 4.0 | 3.4 | 4.0 | 4.3 | 2.7 | 1.5 | 4.0 | 3.0 | 4.7 |
| ROM 400 kg N $ha^{-1}$ | 3.3 | 4.0 | 3.7 | 4.0 | 2.0 | 2.3 | 1.7 | 4.3 | 3.7 | 5.0 |
| **Mean** | **3.8** | **4.1** | **3.9** | **4.1** | **2.5** | **2.3** | **2.0** | **3.6** | **3.8** | **4.7** |
| **$LSD_{(0.05)}$** | **NS*** | **NS** | **NS** | **NS** | **NS** | **NS** | **NS** | **NS** | **NS** | **NS** |
| **CV (%)** | **11.9** | **9.8** | **19.9** | **7.8** | **55.7** | **37.4** | **43.5** | **18.7** | **15.4** | **15.3** |
| **SED** | **0.37** | **0.32** | **0.63** | **0.26** | **1.13** | **0.713** | **0.17** | **0.55** | **0.48** | **0.58** |

**NS*- Not significant**
**Significant $p<0.05$**

Valuation of tea by the Tea Tasters is based on the total score of the assessments in Table 5.1. Tea Tasters' assessment of black tea harvested by hand and machine treatments showed no significant differences in valuation ($p<0.05$) at both sampling dates (Table 5.2). The May 2013 sampling date, representing the off - season period, recorded teas with the highest valuation. Increasing the N-application rate during the main growing period (February 2013) and off - season (May 2013) had no significant impact on valuation, even though the values showed a fair amount of variation. However, in both treatment periods, teas which yielded high scores for organoleptic evaluation (Table 5.1), also recorded high valuation. In the main growing period HHM at 265, 300 and 400 kg N $ha^{-1}$ $yr^{-1}$ recorded high yield, high scores (Table 5.1) and also high valuation (Table 5.2), although at this time hand plucked teas were valued higher.

**Table 5.2 Effect of harvesting method and N-application rate on Tasters' valuation of black tea (US cents $kg^{-1}$ made tea)**

| Treatments | Valuation (US cents $kg^{-1}$ made tea) | | | |
|---|---|---|---|---|
| | February 2013 | | May 2013 | |
| | Total score | Valuation | Total score | Valuation |
| **HP 265 kg N $ha^{-1}$** | 22.3 | 223.0 | 24.3 | 243.3 |
| **HHM 265 kg N $ha^{-1}$** | 20.3 | 203.0 | 23.3 | 233.3 |
| **HHM 300 kg N $ha^{-1}$** | 20.0 | 200.0 | 20.0 | 200.0 |
| **HHM 400 kg N $ha^{-1}$** | 21.7 | 217.0 | 24.0 | 240.0 |
| **ROM 265 kg N $ha^{-1}$** | 19.0 | 190.0 | 23.3 | 233.3 |
| **ROM 300 kg N $ha^{-1}$** | 15.3 | 153.0 | 25.0 | 250.0 |
| **ROM 400 kg N $ha^{-1}$** | 17.7 | 177.0 | 24.0 | 240.0 |
| **Mean** | **19.5** | **195** | **23.4** | **234.0** |
| **$LSD_{(0.05)}$** | **NS** | **NS** | **NS** | **NS** |
| **CV (%)** | **23.5** | **23.5** | **12.3** | **12.3** |
| **SED** | **3.74** | **37.40** | **2.36** | **23.57** |

**NS*- Not significant**
**Significant p<0.05**

#### 5.3.2.2 Made tea density

Made tea density, defined as the volume occupied by 100 g of made tea, was significantly ($p<0.05$) higher in hand plucked bushes (265 kg N $ha^{-1}$) than all machine harvesting treatments in February 2013, except from bushes harvested with the hand held machines and receiving 300 kg N $ha^{-1}$ $yr^{-1}$. However, in May 2013 there were no significant differences in treatments (Figure 5.3). In the off - season (February 2013) lowest density was recorded under the HHM 265 kg N $ha^{-1}$ $yr^{-1}$ (292 $cm^{-3}$ 100 $g^{-1}$) and ROM 300 N $ha^{-1}$ $yr^{-1}$ (298 $cm^{-3}$ 100 $g^{-1}$) harvesting technology. Increasing N-application rates did not seem to have any consistent impact on tea density. Tea density was very similar between the two harvest dates.

#### 5.3.2.3 Percentage Fibre content

The % fibre content exhibited very few significant differences ($p<0.05$) between treatments in either February or May 2013 (Figure 5.4). In February only tea from bushes harvested by ROM, and receiving 265 kg N $ha^{-1}$ $yr^{-1}$, had a significantly higher fibre content than hand plucked bushes. However, in May 2013 only tea from bushes harvested with HHM, and receiving 400 kg N $ha^{-1}$ $yr^{-1}$, had a fibre content higher than hand plucked bushes. Fibre content was higher in February than May for all treatments.

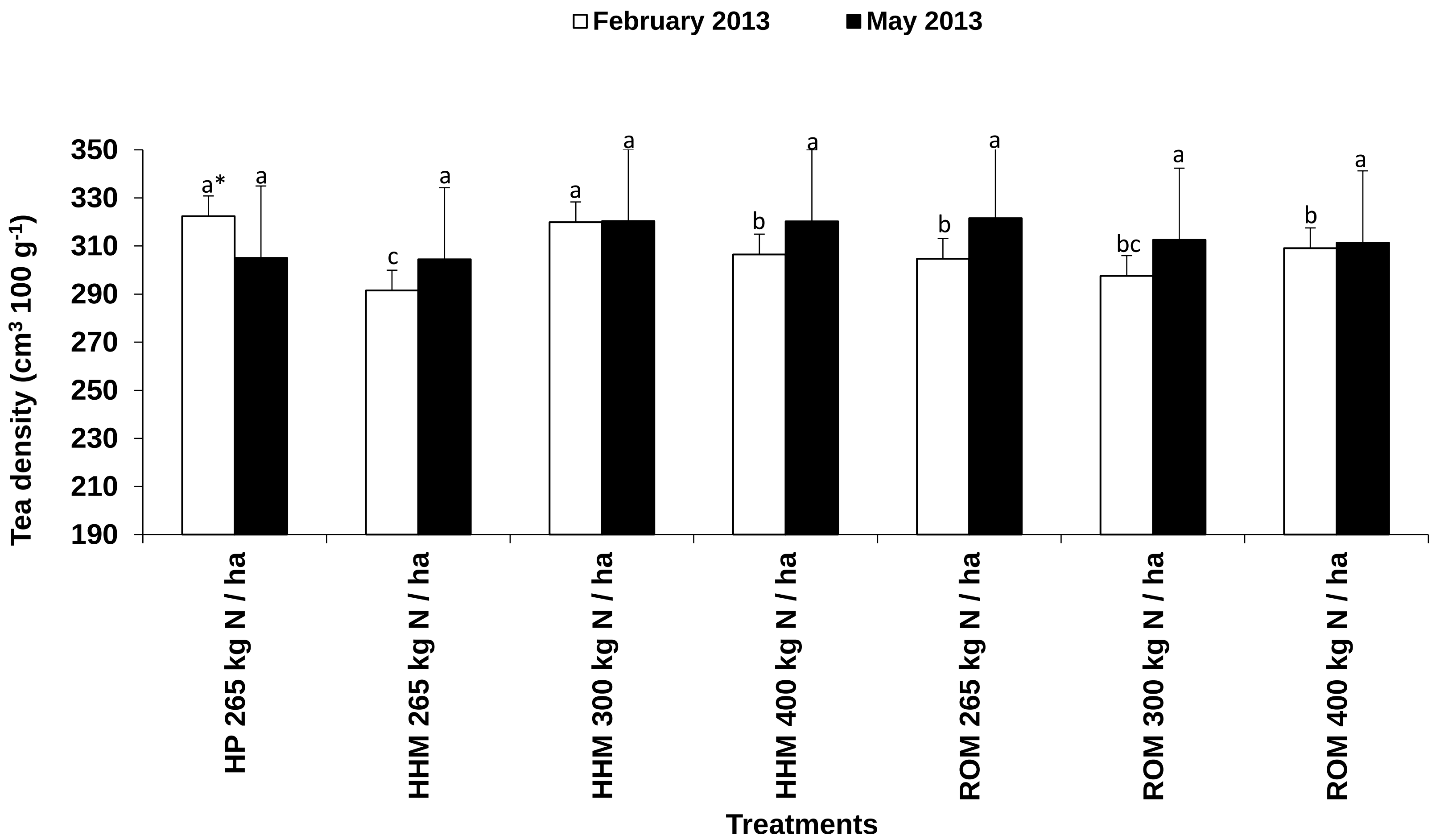


**Figure 5. 3 Effect of harvesting method and increasing N-application rate on made tea density ($cm^3$ 100 $g^{-1}$)**

***Significant at <.05,**
**[1]Means in the same month, followed by the same letter, are not significantly different from each other at p<0.05 05, Duncan's Multiple Range Test (DMRT)**

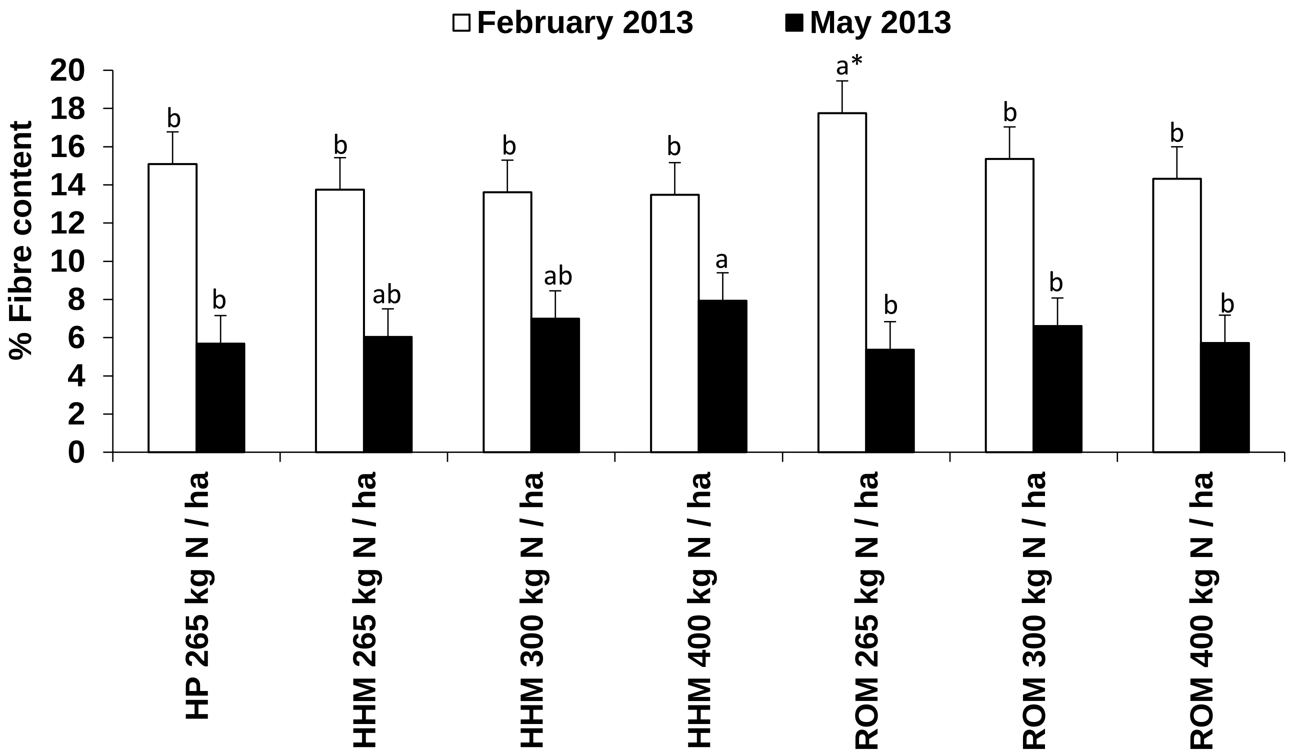


**Figure 5. 4 Effect of harvesting method on made tea fibre content (%) in February and May 2013 sampling dates**

***Significant at <0.05,**
**[1]Means in the same month, followed by the same letter, are not significantly different from each other at p<0.05 05, Duncan's Multiple Range Test (DMRT)**

### 5.3.2.4 Biochemical compounds

Theaflavins (TFs) and Thearubigins (TRs) are important polyphenols that determine brightness, strength and colour of black tea quality. Increasing N-application rates from 265 to 400 kg N $ha^{-1}$ $yr^{-1}$ had no significant effect on the levels of TFs and TRs in February and May 2013 ($p<0.05$) and there were no significant differences between harvesting methods (Table 5.3). However, TFs and TRs were generally higher in samples from May 2013 than from February 2013. The TFs and TRs were generally higher under hand plucking compared to machine harvesting treatment in samples from both February 2013 and May 2013, although these differences were not significant.

**Table 5. 3 Effect of harvesting method and increasing N-application rate on Theaflavins (TFs) and Thearubigins (TRs) (%)**

| Fertilizer rate | February 2013 sampling date | | May 2013 sampling date | |
|---|---|---|---|---|
| | TFs | TRs | TFs | TRs |
| HP 265 kg N $ha^{-1}$ | 0.52 | 7.35 | 0.55 | 9.13 |
| HHM 265 kg N $ha^{-1}$ | 0.46 | 7.05 | 0.50 | 8.73 |
| HHM 300 kg N $ha^{-1}$ | 0.49 | 7.15 | 0.50 | 8.08 |
| HHM 400 kg N $ha^{-1}$ | 0.43 | 6.91 | 0.52 | 8.48 |
| ROM 265 kg N $ha^{-1}$ | 0.47 | 7.02 | 0.52 | 8.83 |
| ROM 300 kg N $ha^{-1}$ | 0.45 | 7.09 | 0.53 | 8.98 |
| ROM 400 kg N $ha^{-1}$ | 0.43 | 7.04 | 0.54 | 8.72 |
| **Mean** | **0.46** | **7.09** | **0.52** | **8.71** |
| **$LSD_{(0.05)}$** | **NS*** | **NS** | **NS** | **NS** |
| **SED** | **0.041** | **0.298** | **0.0327** | **0.498** |
| **CV (%)** | **10.90** | **5.10** | **8.80** | **7.00** |

**NS* – Not significant**
**Significant at P<0.05,**

The relationship between all the most important biochemical markers related to tea quality detected in samples from hand plucked bushes and those from machine harvested bushes are shown Figures 5.5 and 5.6. It was observed that during the main growing period (February 2013) (Figure 5.5) and off - season (May 2013) (Figure 5.6), the Bi-Plots showed that, considering all the markers from biochemical analysis, there were no differences between harvesting techniques and N-application rates and therefore the same type of tea was produced under all the treatments. However, when using a group difference analysis (OPLS-DA) and model mass list a different pattern was observed when considering macromolecules that are specific to black tea quality (Figure 5.7 and 5.8). These molecules and macromolecules include Theanine, Theasinensin A/D, B, C/E, and F/G, Epicatechin, Epigallocatechin, Epigallocatechin gallate, Theaflavin, Theaflavin gallate and Theaflavin digallate. Their masses were used to create the model mass list.

Results show that the production of secondary polyphenols in tea was impacted by both the harvesting techniques and N-application rate interaction. Generally higher levels of the macromolecules were observed under machine harvesting treatments, at higher N-application rates, compared to hand plucking (Figures 5.7 and 5.8). In February 2013 the Theanine levels decreased under mechanical harvesting relative to hand plucking. The levels of Theasinensin C/E, Epigallocatechin gallate, Theaflavin gallate and Theaflavin digallate increased under HHM and ROM at 300 and 400 kg N $ha^{-1}$ $yr^{-1}$ compared to HP 265 kg N $ha^{-1}$ $yr^{-1}$ (Figure 5.7). Theasinensin A/D and Theasinensin F/G levels were low under all treatments (Figure 5.8)

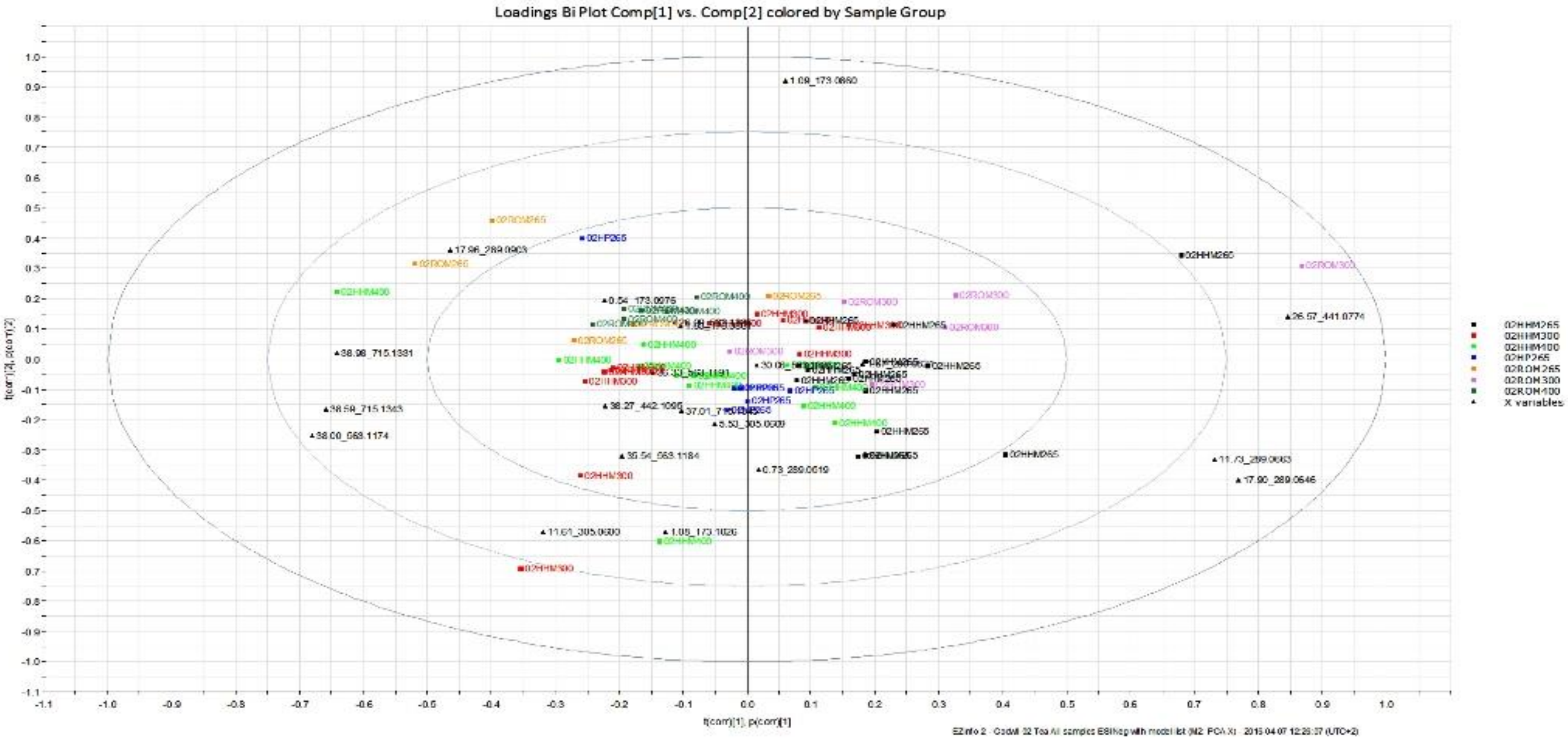


**Figure 5. 5 Bi-Plot showing the relationship between the identified biochemical compounds included in the model mass list and harvesting method, together with nitrogen application rate, for the February sampling period.**

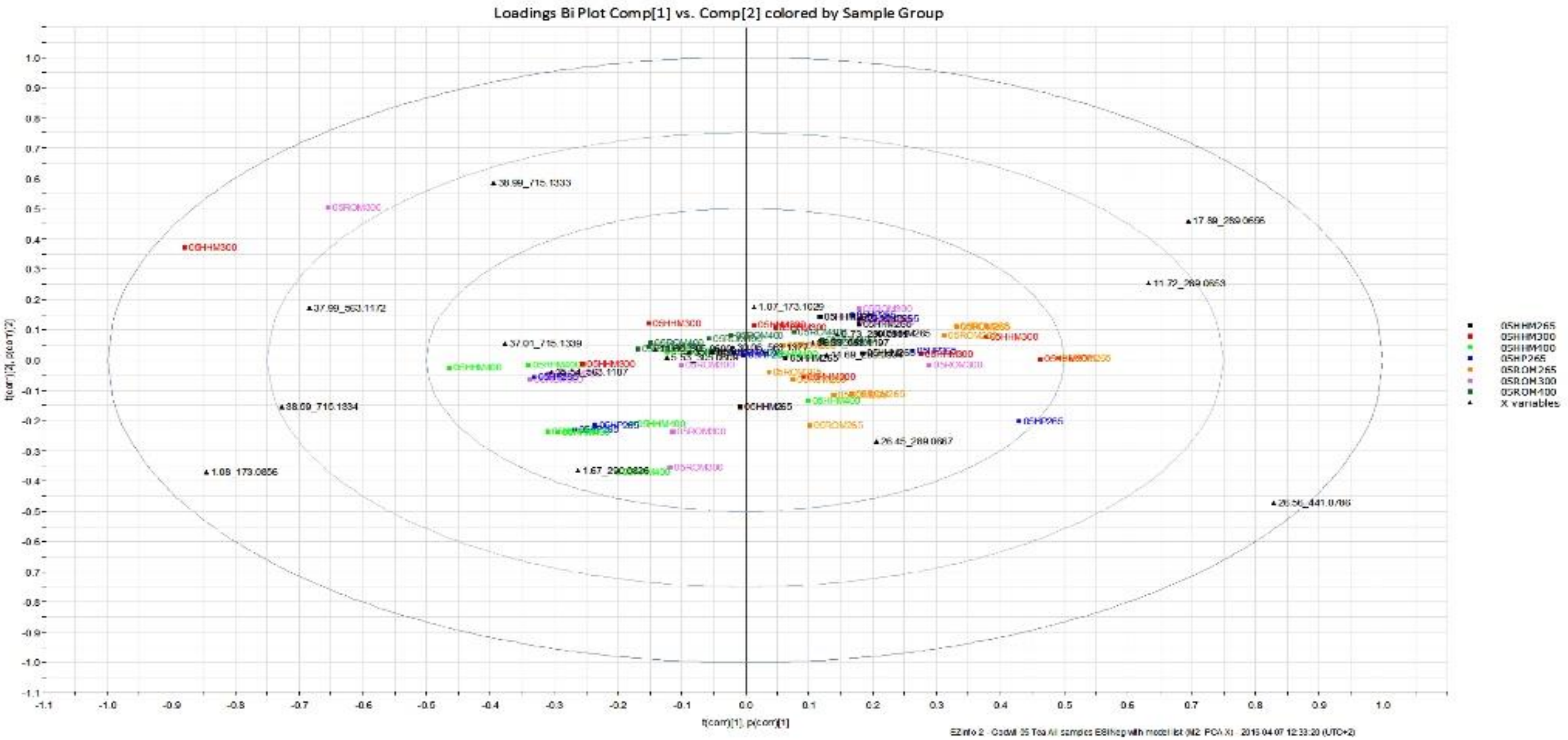


**Figure 5. 6 Bi-Plot showing the relationship between the identified biochemical compounds included in the model mass list and harvesting methods, together with nitrogen application rate, for the May sampling period**

In the off - season (May 2013) the levels of Theanine, Epicatechin, Epigallocatechin and Epicatechin gallate declined under mechanical harvesting treatments relative to hand plucking (Figure 5.8). Theasinensin C/E and Theasinensin A/D levels were generally lower under all harvesting method, although machine harvesting treatments at 400 kg N $ha^{-1}$ $yr^{-1}$ had higher levels compared to hand plucking (Figure 5.8). Theasinensin B levels increased under HHM 400 kg N $ha^{-1}$ $yr^{-1}$ compared to HP 265 kg N $ha^{-1}$ $yr^{-1}$. Theaflavin, Theaflavin gallate and Theaflavin digallate increased with mechanical harvesting and N-application rate. The highest levels of Theaflavin gallate and Theaflavin digallate were recorded during the main growing season compared to the off - season (Figures 5.7 and 5.8), under mechanical harvesting as compared to hand plucking. It was interesting to note that Theaflavin was only detected in the off - season (May 2013) samples, with high levels under HHM and ROM at high N application rates (Figure 5.8).

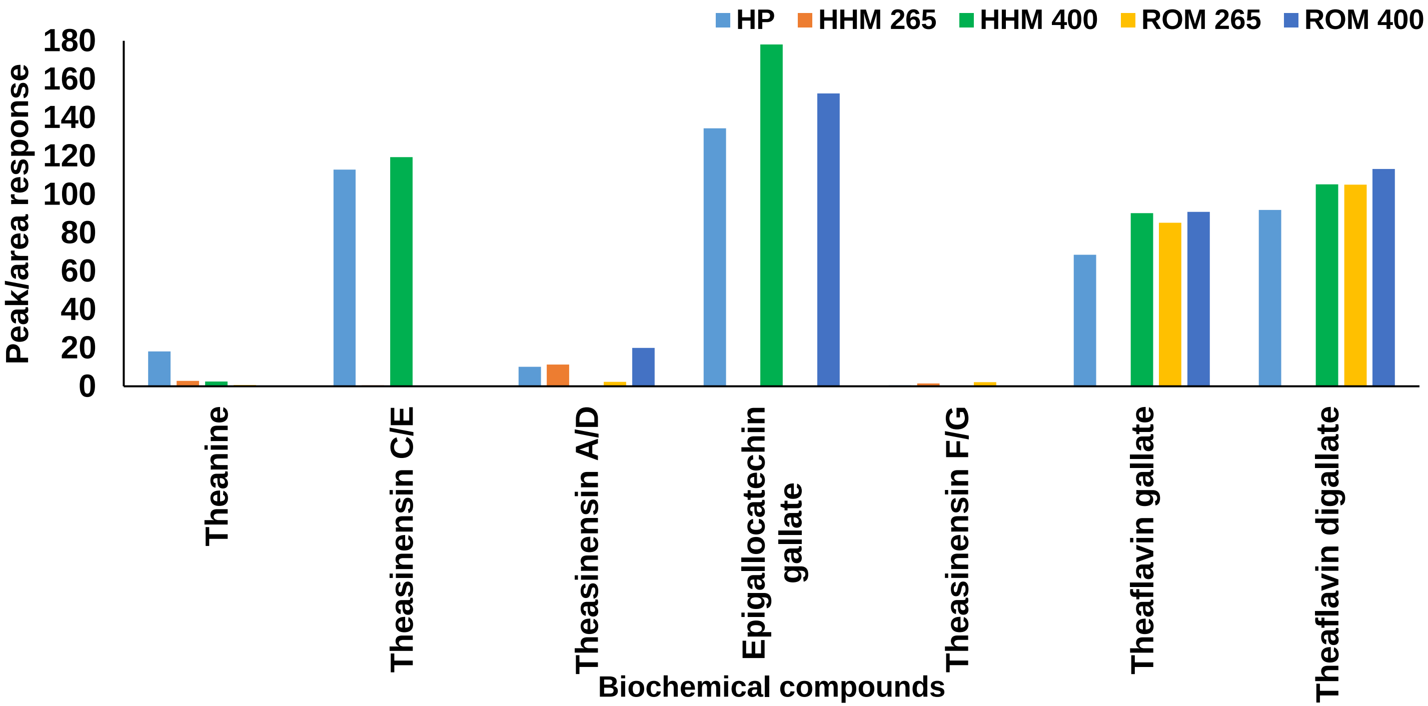


**Figure 5. 7 Effect of harvesting method and N-application rate on production of secondary polyphenols (µmol $g^{-1}$) in the main growing period (February 2013)**

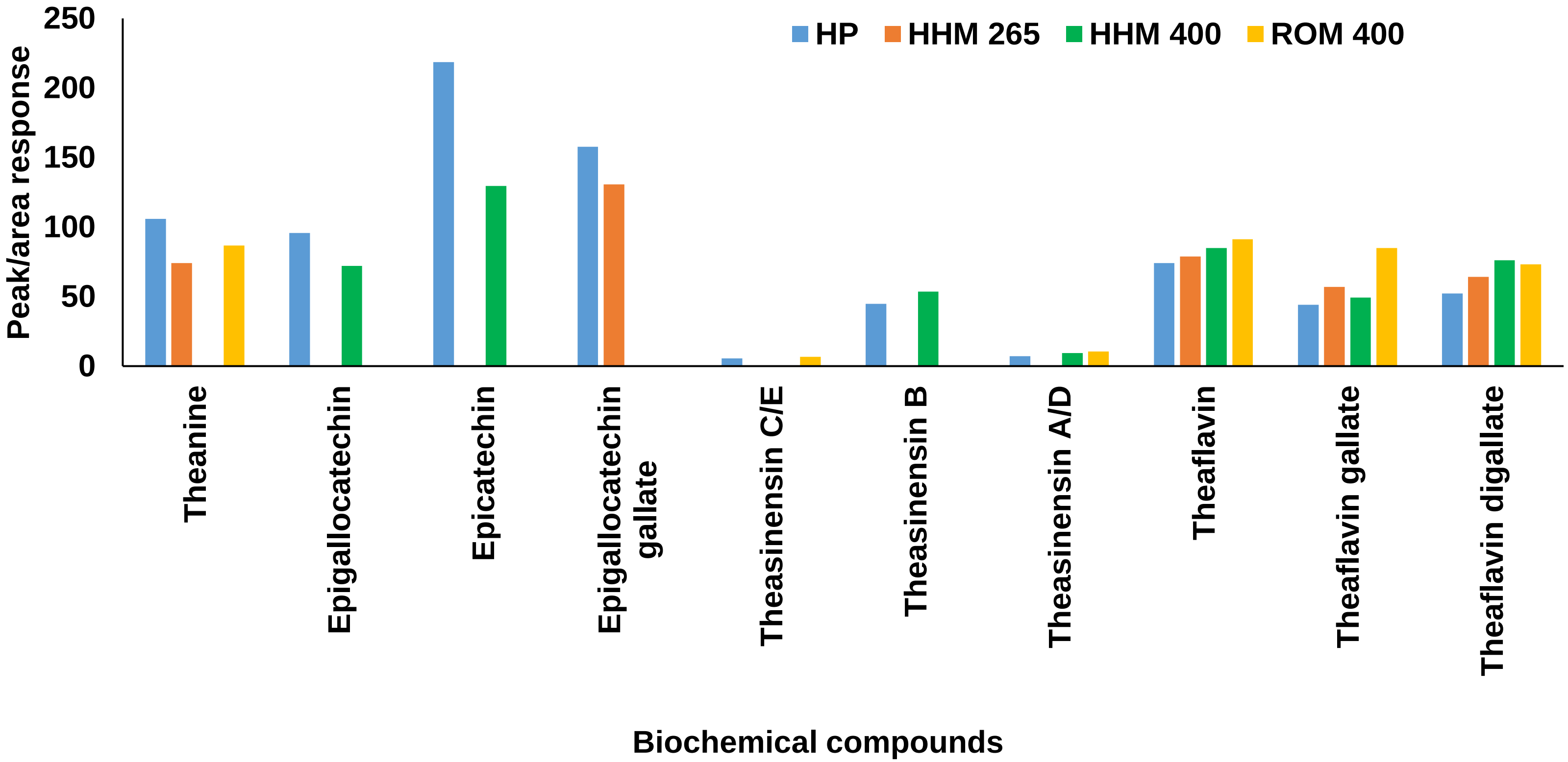


**Figure 5. 8 Effect of harvesting method and N-application rate on production of secondary polyphenols (µmol $g^{-1}$) in the off - season (May 2013)**

### 5.4 Discussion

Profitability of tea is determined by both the yield achieved and the quality of the plucked tea. Whilst this study has shown that yield declined over the three year study period (Chapter 4), the impact of mechanical harvesting on tea quality needed to be established. Quality parameters from tea harvested with machines, at all N application rates, were compared with hand plucked tea at 265 kg N $ha^{-1}$ $yr^{-1}$, which is considered the standard practice on many estates. Hand plucking consistently resulted in higher % good leaf quality across two of the three study seasons, when compared to machine harvesting treatments at 265, 300 and 400 kg N $ha^{-1}$ $yr^{-1}$. This is due to the selective nature of hand plucking for only two or three leaves and a bud (Nandagopalan*, et al.*, 2014), thereby ensuring higher quality as compared to machine harvesting. The non-selective nature of machine harvesting was illustrated in Chapter 4, where a greater number of buds, one leaf and a bud, overgrown 4+b shoots and broken pieces of stem and leaf were observed in machine harvested treatments, as compared to hand plucking (Table 4.2). However, this study showed that in the third season following pruning, the % good leaf quality from machine harvesting treatments equaled that of hand plucking. This was attributed to the impact of the machine harvesting on the bushes and not necessarily an effect of the increase in N application rate, as increasing the N application rate had no impact on % good leaf throughout the three year study period. The observed improvement in % good leaf under machine harvesting in the third season, was most probably due to altering of the plucking table by continuous mechanical harvesting of tea. This allowed only the tender shoots to emerge out of the plucking table, thereby keeping the mother leaf, which form the maintenance layer, in a uniform horizontal plane, which facilitates the harvesting of tender young shoots (Ravichandran & Parthiban, 1998; Nandagopalan *et al.*, 2014). The quality deterioration under continuous mechanical harvesting is therefore expected to normalize with time (Nandagopalan*, et al.*, 2014).

The quality of plucked leaf is known to vary with harvesting policy and plucking standard and these consequently impact the quality parameters of black tea (Kamunya*, et al.*, 2012), such as valuation, made tea density, fibre content and biochemical compounds. Although, % good leaf quality was expected to be poorer under machine harvesting, which would lead to a decline in quality as compared to hand plucking, the study showed that if all the underlying factors that affect quality, such as shoot composition, are addressed, teas of good quality can be achieved using mechanical harvesting. It should, however, be noted that based on the % good leaf and shoot composition results in all three seasons, the quality assessments in the third season (tea tasters' evaluation and biochemical analysis) may not apply to the first two seasons, and as with yield, the possibility of a decline in quality exists in the first two years following pruning.

The constantly changing consumer demands, as well as technological changes and the dominance of tea bags in the developed markets requires certain characteristics of the made tea particles. Made tea should therefore meet specific density values, for example, 245-253 $cm^3$ 100 $g^{-1}$ for the UK market (Jose, 2000). This requirement is to ensure that the high speed packing machine can function properly. If density of tea is low, more volume is needed to meet the required weight of 3.125 g per tea bag (Jose, 2001b), leading to overfilling of the bag, with consequential sealing problems and possibility of rupture. However, if the density is too high only part of the bag is filled when the required weight is met (Jose, 2000). Hand plucking resulted in teas of higher densities in February compared to the machine harvested treatments, with no significant differences between the harvesting treatments in the off - season. The lack of selectivity of machine harvesting results in the harvesting of overgrown shoots which are more fibrous due to increased internodal extension (Jose, 2001b, Kottur*, et al.*, 2010). This lowers the density under machine harvesting, whereas in May growth is slow due to reduced internodal extension and less fibrous shoots are produced. As a result teas of higher density are produced. Tea density under mechanical harvesting was, however, within the same acceptable values as hand plucked tea, as used by Tanganda Tea Company for primary (Broken Pokoe- 335-365; Broken Pokoe1- 305-335; Pekoe Fannings 1- 275- 300; Pekoe Dust- 215 -265 $cm^3$ per 100 g) and secondary grades (Dust- 2 205-225; Fannings 2- 265- 325 $cm^3$ per 100 g) (Tanganda Tea Company Tea grading specification, 2011) and also as recommended in Malawi (BP1 300-350 $cm^3$ per 100 g, PF1 260 and PD 230-260) (Jose, 2001b).

The results from the study showed a higher % fibre content in February when fast growth was observed due to the increased growth of internodes, as compared to May 2013, which was considered the off - season. According to Jose (2000), this could be due to the production of more fibre in the stems. The rapid fast growth in the main growing period results in increased internodal extension and as a result stem tissue accounts for most of the increased fibre content in February as compared to May. The fibre content of treatments varied from 5 to 15 % with the exception of ROM 265 kg N $ha^{-1}$ $yr^{-1}$ where the fibre content was 17%. These values fall within the % fibre limit fixed around 16% for Malawi and Indian tea industries (Ravichandran and Parthiban, 1998, Jose, 2001b).

The results of organoleptic evaluation showed that neither harvesting method nor N-application rate impacted liquor colour, liquor strength, briskness, brightness and colour of infusion in the main growing period (February 2013) and off - season (May 2013). Although there was variation in the price realization of black tea quality parameters, there were no significant differences between treatments, indicating that harvesting method and N-application rate had no impact on the valuation of the manufactured tea. There was, however, variation between the main and off - seasons i.e. February and May. Teas produced during the off - season (May 2013) were generally valued higher than the teas in the main growing period (February 2013). The teas that were produced during the off - season (May 2013) under all harvesting treatments exhibited a good coppery red colour and were bright and brisk, which could have led to the higher valuation of these teas. This is in agreement with the TRFCA definition of tea quality, which can generally be described as being plain (without aroma), characterized by coppery red colour of the infused leaf, with its liquor being bright, strong and brisk and taking milk well (TRFCA, 2013a). Importantly, overall results of organoleptic evaluation based on total score and valuation showed that the quality of machine harvested teas were not poorer compared to hand plucked teas.

A more detailed metabolite analysis of the tea samples confirmed that the teas from the different treatments were very similar, as there was no definitive clustering of the various treatments in the Bi-Plots. However, a more detailed analysis of some of the important macromolecules, which are formed during the fermentation process and therefore contribute to the quality of black tea, revealed a very interesting trend. Higher levels of these macromolecules were noted in teas from machine harvested bushes receiving high N-application rates, as compared to tea from hand plucked bushes. Theanine, Epicatechin, Epigallocatechin and Epicatechin gallate levels declined under mechanical harvesting relative to hand plucking. However, the levels of Theaflavin,

Theaflavin gallate and Theaflavin digallate increased with mechanical harvesting and N-application rate relative to hand plucking. This is to be expected due to the depletion of these molecules during the formation of the associated macromolecules. These macromolecules (Theaflavin, Theaflavin gallate and Theaflavin digallate) are dimers and trimers of the different catechins (Epicatechin, Epigallocatechin and Epicatechin gallate) and were probably formed by enzymatic reactions involving polyphenol oxidase (PPO) (Wright*, et al.*, 2002, Bhuyan*, et al.*, 2015) which took place soon after harvesting and thereby starting what is erroneous known in the tea industry as "field fermentation". According to Tanaka*, et al.* (2009), the polyphenols/ macromolecules are stable as long as they are accumulated in living plant cells. However, when the tissues undergo physiological changes, such as wounding of the tissue by herbivores, some of the polyphenols are chemically converted to secondary polyphenols by enzymatic and non-enzymatic reactions. In this case, due to the non-selective harvesting by machine, which often results in cut leaf, these enzymatic reactions begin soon after harvest. In hand plucked tea these processes only begin during maceration in the factory. The production of these macromolecules is therefore most probably enhanced in mechanically harvested bushes as evidenced in the study. The higher levels of Theaflavins, Theaflavin gallate, Theaflavin digallate and Theasinensin, which contribute to the red colour of the liquor and the lower % fibre content would have resulted in higher pricing during this time of the year. This is in agreement with studies done in south India, where it was reported that low fibre content results in higher price realization (Kottur, *et al*., 2010). The combined effect of these macromolecules could have increased the black tea quality as was noted by Wright*, et al.* (2002), who concluded that the quality of central and southern African teas is more dependent on the total amount of Theaflavins. The higher levels of these compounds under machine harvesting could have increased the black tea quality, reducing the perceived negative effect of machine harvesting on tea quality.

**5.5 Conclusions**

In the third season after pruning there were no differences in tea quality between hand plucked and machine harvested teas. However, as indicated by the differences in % good leaf between the seasons, this might not have been the case for all three seasons and there is a need for a more exhaustive study on the effects of mechanical harvesting on tea quality throughout the pruning cycle. It is also unlikely that increasing

N application rates would have an impact on quality as there was no change in % leaf quality throughout the study as a result of increasing N application rates. Organoleptic evaluation of the made tea showed that tea harvested by hand and machines did not differ in terms of liquor colour, liquor strength, briskness, brightness, colour of infusion, valuation and total score. The percentage fibre and the made tea density did not differ between hand plucking and machine harvesting treatments and were all within acceptable % fiber content limits, as dictated by the tea industry in Zimbabwe and Malawi. Although a general metabolite comparison of teas from all treatments revealed that there were no differences between the various teas, a more in depth analysis revealed some significant trends. The concentration of dimers and trimers of smaller catechins increased under mechanical harvesting and high N-application rates. The only exception was Theanine, Epigallocatechin, Epicatechin and Epigallocatechin gallate, which declined under mechanical harvesting under all fertilizer levels. This was due to the depletion of these compounds due to the increased formation of the associated macromolecules. These studies on PC 108 have shown that in those regions, like Malawi and Zimbabwe where labour is unavailable and/or expensive, mechanical harvesting of tea can be used as an alternative to hand plucking without compromising green leaf quality, valuation, made tea density, % fibre content and biochemical compounds. It is, however, important to note that to get the full benefit of mechanical harvesting, in terms of black tea quality, proper handling and managing of the tea harvesters is of utmost importance. Accordingly to Wijeratne (1999), reduced handling of mechanically harvested leaf resulted into superior leaf quality compared to hand plucking. This can be achieved by avoiding over packing of plucking baskets, avoiding double handling the leaf through sorting of the leaf before loading into trailers and compressing of the leaf in trailers in order to load more leaf.

It is important in future to study the production of these macromolecules under the different harvesting methods and their overall effect on quality and price over a longer period of time, instead of the two month period as in this study, as these compounds make an important contribution to black tea quality. In addition, there is a need to determine how the different harvesting methods affect chlorogenic acid profiles and volatile flavour compounds, as mechanical harvesting causes more mechanical injury to the leaves and bushes compared to hand plucking. These compounds are responsible for the taste and aroma of black tea (Bhuyan, *et al.*, 2015). The hypothesis that continuous mechanical harvesting can be used as an alternative to hand plucking and does not lead to a reduction in black tea parameters is accepted.

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# CHAPTER 6

# Increased nitrogen application rate mitigates yield decline caused by continuous mechanical harvesting of cultivar tea (*Camellia sinensis* (L) O. Kuntze)

## 6.1 Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is grown as a perennial long term monoculture that can be in economic production for over 100 years, if well managed by annual fertilization and periodic pruning to form an even plucking table, facilitating hand or mechanical harvesting (Kamau*, et al.*, 2008). Harvesting of tea has traditionally been a labour intensive operation, accounting for more than 40% of the total field costs (Burgess*, et al.*, 2006). The ever increasing cost of labour and its unavailability, together with increased cost of production, resulted in tea industries in central and southern Africa becoming unprofitable. As a result the tea industry began full mechanization of shoot harvesting, but a decline in yield and quality was soon observed (Madamombe*, et al.*, 2015). The observed decline in yield in mechanically harvested bushes was due to the indiscriminate removal of foliage by the machines, which altered canopy architecture, as compared to hand plucked bushes, resulting in a decrease in the interception of photosynthetically active radiation (PAR) in the top 10 cm of the canopy (Madamombe*, et al.*, 2015). This reflected a depleted maintenance layer, which when linked to lower light-saturated photosynthetic rates equated to a less active maintenance layer in these bushes, with the implication that these bushes were source limited. Shoot growth was further compromised in these bushes due to the presence of larger numbers of immature shoots (buds and 1 + b), which are strong sinks, resulting in increased competition between these shoots for an already depleted assimilate supply (Madamombe*, et al.*, 2015). The depleted maintenance layer could lead to poor leaf distribution, as observed in machine harvested fields. As a result the growth of new shoots was retarded, resulting in fewer desirable shoots of lower mass during each season, hence the reduced yield (Nandagopalan*, et al.*, 2014, Madamombe*, et al.*, 2015). Despite initial perceptions that quality also declines in mechanically harvested tea bushes, results in Chapter 5 indicate that quality did not decline under mechanical harvesting.

The indiscriminate removal of foliage under mechanical harvesting results in the continuous harvesting of young harvestable tender shoots which contain the greatest concentration of N (Dang, 2005, Kamau*, et al.*, 2008). Thus the removal of N through harvesting is bound to be greater under continuous mechanical harvesting, as compared to traditional hand plucking, due to the greater number of young shoots being harvested by machines. The high nutrient requirements for commercial tea production, and the incredibly positive response of tea to N supply, is most probably attributable to the frequent loss of N through harvesting of shoots, whose N content is approximately 4 to 5% (Dang, 2005, Cheruiyot*, et al.*, 2010). Even though a positive tea yield response to N supply rate of up to 500 kg N $ha^{-1}$ $yr^{-1}$ has been reported, N-application rates rarely exceed 300 kg N $ha^{-1}$ $yr^{-1}$, partly due to the negative effect of high N on plain black tea quality (Cheruiyot*, et al.*, 2010). Consequently, the recommended N-application rate that gives the best compromise between yield and quality of black tea ranges from 150 to 200 kg N $ha^{-1}$ $yr^{-1}$ in Kenya (Cheruiyot*, et al.*, 2010), 250 to 450 kg N $ha^{-1}$ $yr^{-1}$ in Australia (Drinnan, 2008), 225 to 300 N $ha^{-1}$ $yr^{-1}$ for Malawi and Zimbabwe (Drinnan, 2008) and 1200 kg N $ha^{-1}$ $yr^{-1}$ for green tea in Japan (Watanabe, 1995).

Fertilization plays a vital role in the economic production of tea. Bonheure and Willson (1992), reported that without fertilizer application, the continued removal of N through the young vegetative shoots at harvest, would exhaust the supply of available nutrients in the soil, leading to mineral deficiencies in plants, severe reductions in yield and ultimately death of plants. There is therefore need for the continued replenishment of N for growth of new shoots through external application. Low levels of nitrogen have also been shown to negatively affect both the source and sink capacity of tea by decreasing the formation of photosynthetic components (and thus photosynthetic rate) and shortening the productive life-span of leaves (Mohotti and Lawlor, 2002). The number and size of shoots have also been shown to decrease as a result of non-selective harvesting which removes mature and immature shoots, thereby limiting sink capacity for the utilization of assimilates (Mohotti and Lawlor, 2002, De Costa*, et al.*, 2007). As a result carbohydrates accumulate, and may lead to feedback inhibition of photosynthesis and photoinhibition (Mohotti and Lawlor, 2002).

The impact of mechanical harvesting on the N balance of the tea bush is not well understood. There is wide gap in knowledge of how tea bushes respond to N fertilization under continuous mechanical harvesting, despite the large amount of information on how N affects yield and quality of tea (Drinnan, 2008). As mechanical harvesting is non-selective, all available shoots are removed, even immature ones, which remain on the bush under hand plucking and contribute to the next generation of harvested shoots (Nandagopalan*, et al.*, 2014). These young immature and harvestable shoots contain the highest N content (Dang, 2005, Kamau*, et al.*, 2008). It was therefore hypothesized that a contributing factor to the yield reduction under mechanical harvesting is high N removal rates which are not replaced using the current recommended N-application rates. Higher N-application rates could therefore possibly mitigate against the yield decline in mechanically harvested tea bushes with little environmental impact through nitrate leaching. However, as N is known to impact quality of tea, increased N-application rates should not have a negative impact of tea quality. This study aimed to determine the response of tea bushes to varying N-application rates under continuous mechanical harvesting and to monitor changes in leaf and soil nutrient status over a three year pruning cycle in the blocks of tea receiving different N-application rates.

## 6.2 Materials and Methods

### 6.2.1 Field site description

The study site is described in Chapter 3 Section 3.1. Data on the mean monthly rainfall and temperature and monthly and seasonal rainfall totals of the study site for the 2010 to 2013 growing seasons are presented in Figure 6.1.

### 6.2.2 Field trials and treatments

Chapter 3.2 gives a detailed account of the experimental design, showing the different fertilizer splits, application dates and treatment combination.

### 6.2.3 Yield determination

Hand plucking was performed every 10/11 days and machine harvesting (hand-held and ride-on machine) every 14 days for tea yield determination. The total monthly green leaf yield data per plot over the three year study period was converted to kilograms of made tea (mt) per hectare per year (kg mt $ha^{-1}$ $yr^{-1}$) using the formula:

$$\text{Made tea yield} = \frac{\text{Green leaf yield mass per plot} \times \text{No. of bushes per ha} \times 0.225}{\text{No. of bushes per plot}}$$

0.225 is the factor converting green leaf yield to made tea (De Costa, *et al.*, 2007, Njogu, *et al.*, 2015, Sitienei, *et al.*, 2013, Wachira, 1994).

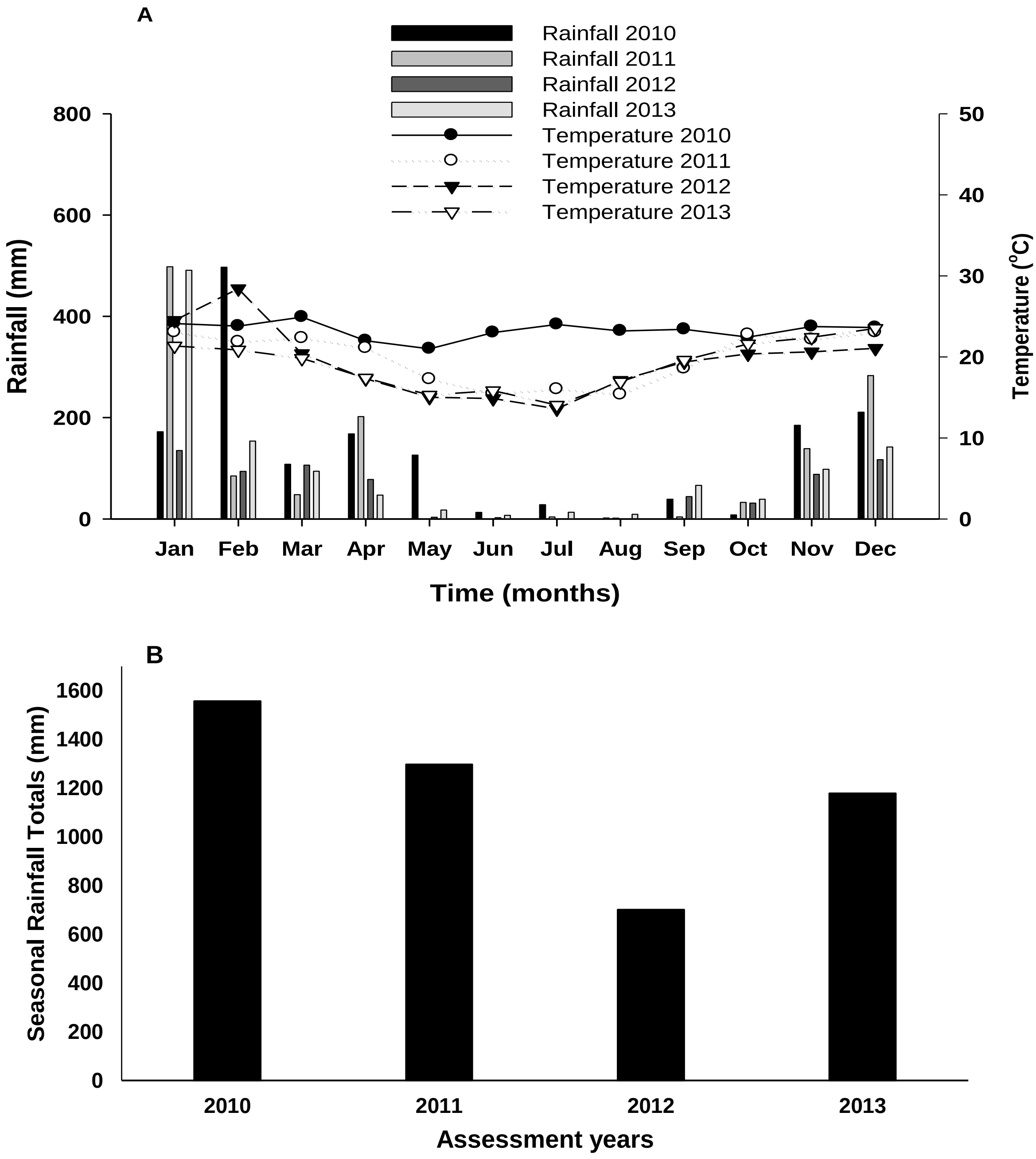



**Figure 6. 1 A) Mean monthly temperature (lines) and total monthly precipitation (bars) and B) yearly rainfall totals recorded in the 2010 to 2013 seasons**

### 6.2.4 Green leaf determination

Percentage green leaf was determined using the method described in Chapter 3 Section 3.5.1.

### 6.2.5 Soil sampling

Six soil core samples were collected randomly from each layer of a plot for all treatments at the beginning of the study (before treatment application in June 2010 for uniformity studies) and at the end of each growing season (June 2011, June 2012, and June 2013). The uniformity studies showed that the nutrient status of the soil was not significantly different between the seven treatments at the start of the experiment. The soil samples were collected from the 0 – 0.2 m and 0.2 – 0.4 m soil layers. The replicate samples from each layer of the same plot were combined and mixed to make a single homogeneous soil sample. All soil samples were dried and pulverised to pass through a 2 mm sieve. The dried and ground soil samples of the 0 – 0.2 m soil layer were digested and analysed for N, P, K, S, Zn, Cu, Mg, Fe, B, and Al. The samples were also analysed for pH and soil texture. Soil samples collected from the lower 0.2 – 0.4 m soil layer were, however, analysed only for N for the purpose of this study.

### 6.2.6 Plant sampling

Leaf samples were collected from the study area in January 2010, 2011, 2012 and 2013 with the samples being collected from the same marked positions, corresponding to where soil sampling was done, for consistent and reliable results. A total of 10 leaf samples were collected randomly from two bushes per plot of each treatment in each replicate at the second flush according to the procedures prescribed by Grice (1990). A total of 30 leaves were collected for each treatment. The leaf samples from each bush were collected from the third leaf of a flushing shoot. Leaf samples were oven-dried at 70 °C for at least 48 h and then finely ground using a coffee-grinder and/or mortar and pestle (Berner and Law, 2016) to pass through a 2 mm sieve before digestion for chemical analyses.

### 6.2.7 Plant and soil chemical analyses

Nitrogen content of tea leaf samples were determined on 0.25 g sub-samples according to the macro dry combustion method using the LECO CNS-2000 Analyzer (Medina*, et al.*, 2015, Berner and Law, 2016). Total N content of soil samples was determined colorimetrically using the Kjeldahl digestion method (Hue*, et al.*, 2000, Sitienei*, et al.*, 2013). Inorganic N content of soil samples was determined using 2N KCl as described by Dorich and Nelson ( 1984). All analytical analysis was done at Aglabs laboratories, Harare, Zimbabwe

**6.2.8 Monitoring of nitrate leaching**

Nitrate concentration of the soil solution was monitored using FullStop Wetting Front Detectors (WFD) which were installed in the middle of each experimental plot, where 400 kg $ha^{-1}$ $yr^{-1}$ of N was applied. WFDs were placed at 0.2 m and 0.6 m depth in all treatments. The limited number of WFDs meant that all treatments could not be instrumented for all depths. A WFD is a funnel-shaped passive lysimeter used for managing irrigation, salinity and nutrition (Fessehazion*, et al.*, 2011, Stirzaker, 2003, Stirzaker and Hutchinson, 2006, Tesfamariam*, et al.*, 2015). When the soil around the WFD approaches 2 to 3 kPa suction during or shortly after irrigation or rainfall, free water is produced at the base of the funnel (Fessehazion*, et al.*, 2011, Tesfamariam*, et al.*, 2015). This free water flows through a filter into a small reservoir and activates a float, which is visible above the soil surface (Stirzaker*, et al.*, 2010). Normally 20 ml must collect in the reservoir to trip the float (Stirzaker, 2003), however, this depends on soil type. In this study it was observed that 40 mm rainfall or irrigation, was enough to activate the floats of the WFDs installed at 0.2 m depth. This free water was extracted from the reservoir using a syringe. In this study the samples collected from the WFDs were analyzed for nitrate concentration using a RQflex 10 Easy Nitrate reflectometer (Merck KGaA, Germany).

Soil core sampling was done to a depth of 1.5 m to determine the rooting zone of tea and the majority of tea feeder roots were found in the region between 0.10 and 0.20 m. This is in agreement with previous reports of Niranjana and Viswanath (2008), who found most tea feeder roots in the top 0.45 m of the soil. Although rooting depths of >5 m have been reported in Malawi, Kenya and Tanzania (Carr, 2012), for the purpose of this study only nitrate leachate collected from the WFDs buried 0.2 and 0.6 m beneath the soil surface will be presented.

### 6.2.9 Cost analysis

The important parameters for the economic analysis are the price of N (29 % N) in the T-blend fertilizer per tonne, the price of a 50 kg fertilizer bag, the cost of N in the 50 kg bag and the price of made tea in addition to the tea yields for the different fertilizer rates (265, 300 and 400 kg N $ha^{-1}$ $yr^{-1}$). These prices are important in determining the cost of a kg N in the fertilizer blend. At the time of the experiment T-blend fertilizer cost $780 per tonne, 1 x 50 kg bag cost $39.10, with the price of 14.5 kg N in the 50 kg bag costing $11.34. Therefore the cost of 1 kg N was calculated to be $0.78. Taking 265 kg N $ha^{-1}$ $yr^{-1}$ as the baseline for all calculations, the additional amount and cost of fertilizer was determined by subtracting the higher rates (300 and 400 kg N $ha^{-1}$ $yr^{-1}$) from the base rate of 265 kg N $ha^{-1}$ $yr^{-1}$. Multiplying this figure by the cost of N per kg ($0.78) gave the cost of the additional fertilizer. The price of made tea was $1.20 per kg made tea and yield data for the different fertilizer treatments was used to determine the income from the tea sales. By computing the difference in income from the fertilizer purchased for the different treatments using the same harvesting method, the income as a result of the additional fertilizer applications was determined. The return per dollar invested was finally determined by dividing the income as a result of the additional fertilizer application by the cost of the additional fertilizer applied.

## 6.3 Statistical analysis

Analysis of variance (ANOVA) on yield, foliar, soil and nitrate N analysis and generation of graphs was performed for a factorial and added control experiment in a randomized complete block design using Genstat 14th edition computer statistical package (Payne et al., 2011), with the probability limit set at $p<0.05$. To be able to apply ANOVA on the combined data to test for differences between the harvesting method treatments, as well as the treatment × year interaction, the combined data were analyzed as repeated measurements. Separation of treatment means was performed using Fishers least significant differences (LSD). Sigma plot 8.0 was used to generate graphs.

## 6.4 Results

### 6.4.1 Yield

When yield data was combined for the three years and three fertilizer treatments, there was no significant ($p > 0.05$) interaction for tea yield. There was, however, a significant ($p < 0.05$) year x harvesting method interaction for tea yield (Table 6.1). The year x harvesting method interaction shows a generally similar yield ranking of harvesting method treatments for each year. This shows that the interaction was caused primarily by the magnitude of yield differences between the years. However, there was no significant ($p > 0.05$) year x fertilizer interaction effect on tea yield.

**Table 6. 1 Degrees of freedom, mean squares, and F probabilities for the combined analysis of variance for yield, harvesting methods and fertilizer rates at Tingamira Estate, Chipinge, Zimbabwe from 2011 to 2013.**

| Source of variation | df† | Mean square Yield (kg mt ha$^{-1}$) |
|---|---|---|
| Harvesting method (HP vs MH) | 1 | 2 699 272** |
| HP vs HHM vs ROM | 1 | 92 399 NS |
| Fertilizer rates | 2 | 1 683 060** |
| Harvesting method vs fertilizer rate | 2 | 125 795 NS |
| **Error (a)** | **12** | **124 148** |
| year | 2 | 8 753 510** |
| Year x harvesting method (HP vs MH) | 2 | 595 056** |
| Year x HP vs HHM vs ROM | 2 | 278 083* |
| Year x fertilizer rates | 4 | 131 094 NS |
| Year x harvesting method vs fertilizer rate | 4 | 44 336 NS |
| **Error (b)** | **28** | **57 980** |

*** Significant at the 0.05 level of probability.**
**** Significant at the 0.001 level of probability.**
**NS - Not significant**
**† df - degrees of freedom.**

Generally, high N fertilization application rates of 400 kg ha$^{-1}$ yr$^{-1}$ significantly ($p<0.05$) increased tea yield, compared with the 265 and 300 kg ha$^{-1}$ yr$^{-1}$ N-applications throughout the study period (Figure 6.2). The only exception was during the 2010/2011 growing season, where the yield difference between the 400 and 300 kg ha$^{-1}$ yr$^{-1}$ N-applications were not statistically significant (p>0.05) (Figure 6.2). Yield was higher during the 2011/2012 growing season than 2010/2011 and 2012/2013 (Figure 6.2). The greatest difference in yields between the different N-application rates was observed in the 2012/2013 when tea yield from the 400 kg N ha$^{-1}$ yr$^{-1}$ treatment was 25% higher than the 265 kg N ha$^{-1}$ yr$^{-1}$ treatment and 24% higher than the 300 kg N ha$^{-1}$ yr$^{-1}$ treatment. In the other seasons yield from the plots receiving the highest N-application rate was on average 14% higher than plots receiving the lower N-application rates.

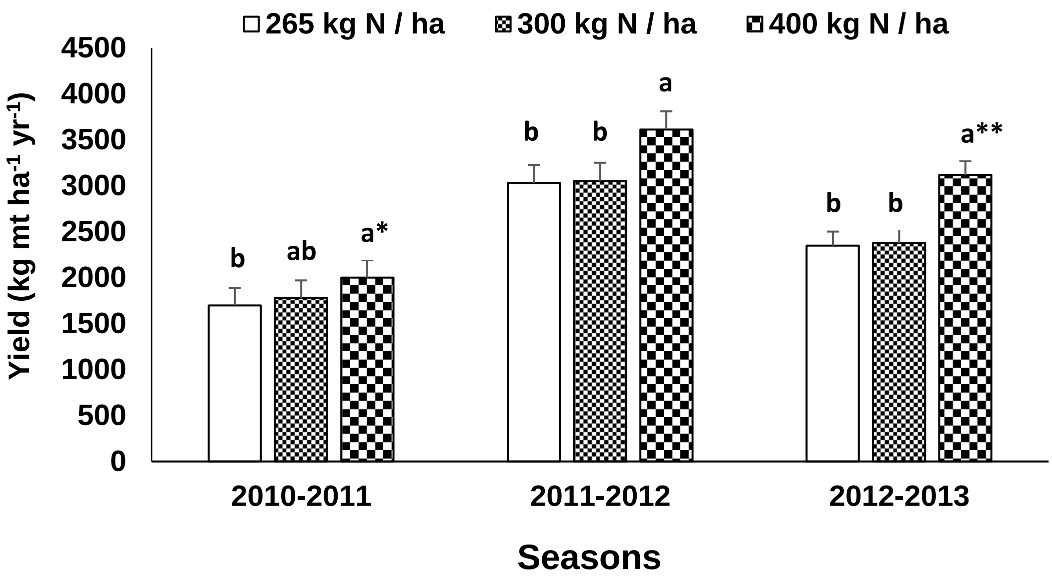



**Figure 6. 2 Effect of increasing N-application rate on made tea yield (kg made tea ha$^{-1}$ yr$^{-1}$) under machine harvesting across the different harvesting seasons (p<0.05)**

***Means followed by the same letter in the same year are not significantly different from each other at p<0.05 Duncan's Multiple Range Test (DMRT)**
***p<0.05**
****p<0.001**

In the 2010/2011 season HP resulted in significantly higher yields compared with machine harvesting treatments (*p*<0.05) (Figure 6.3). However, in the 2011/2012 and 2012/2013 seasons yields under machine harvesting equaled or even surpassed that of HP (Figure 6.3). Hand plucking, with an N-application rate of 265 kg N ha$^{-1}$ yr$^{-1}$, is the standard practice followed on many estates and consistently produced higher yields across the three seasons when compared to machine harvesting treatments at

265 and 300 kg N ha$^{-1}$ yr$^{-1}$ (Figure 6.3). In the 2011/2012 and 2012/2013 seasons yield plots harvested with ROM, with an N-application rate of 400 kg N ha$^{-1}$ yr$^{-1}$, exhibited significantly higher ($p<0.05$) yields (3749 and 3217 kg mt ha$^{-1}$ yr$^{-1}$ respectively) than plots harvested with HHM, also receiving 400 kg N ha$^{-1}$ yr$^{-1}$ (3476 and 3021 kg mt ha$^{-1}$ yr$^{-1}$ respectively) and hand plucked plots (3578 kg mt ha$^{-1}$ yr$^{-1}$). Importantly, increasing the N-application rate in the HHM and ROM plots to 400 kg N ha$^{-1}$ yr$^{-1}$, increased yields in the machine harvested plots to levels similar to or higher than the hand plucked plots in the 2011/2012 and 2012/2013 seasons (Figure 6.3).

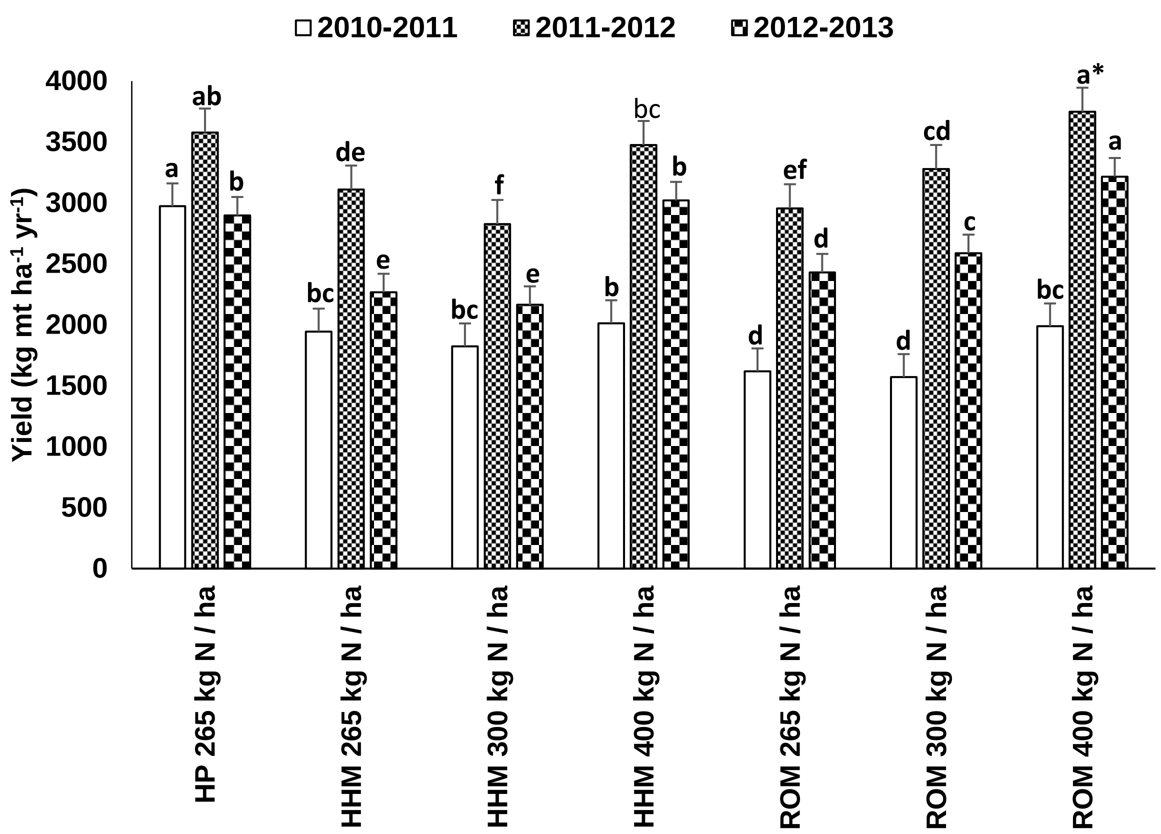



**Figure 6. 3 Effect of increasing N-application rate on yield (kg made tea (mt) ha$^{-1}$) under the different harvesting methods ($p<0.05$)**

**HP= hand plucking, HHM= hand held machine, ROM= ride on machine**

***Means followed by the same letter in the same year/season are not significantly different from each other at p<0.05. Duncan's Multiple Range Test (DMRT)**

Seasonal yield analysis showed peaks and troughs in yield throughout the study period. However, the overall patterns of growth were quite similar for each season, with the highest yields from October to April, with very low yields from May to September (Figure 6.4). Over the three year study period, the highest yields, on a monthly basis, were produced under machine harvesting treatments with 300 and 400 kg N ha$^{-1}$ yr$^{1}$ compared to hand plucking. The highest monthly yields followed fertilizer applications and rainfall events (Figure 6.1). In December 2011 the highest yields for the season were recorded in the HHM and ROM receiving 400 kg N ha$^{-1}$ yr$^{-1}$ (5708 and 5383 kg mt ha$^{-1}$ yr$^{-1}$), which was a month after fertilizer application (10 November 2011) and during a period when 283 mm of rainfall was recorded. At this time the lowest yield (3735 kg mt ha$^{-1}$ yr$^{-1}$) was recorded from the ROM 265 kg N ha$^{-1}$ yr$^{-1}$ plots. In the 2012/2013 season several peaks in yield were observed, which was in contrast to the previous two seasons. The highest monthly yield (3755 kg mt ha$^{-1}$ yr$^{-1}$) for the hand plucked plots was observed early in the season in December 2012, at a time when low yields (1022 kg mt ha$^{-1}$ yr$^{-1}$) were recorded in the HHM 265 kg N ha$^{-1}$ yr$^{-1}$. Yields in the ROM 400 kg N ha$^{-1}$ yr$^{-1}$ treatment reached a maximum for this season a month later in January 2013, whilst for the HHM 400 kg N ha$^{-1}$ yr$^{-1}$ yields peaked in March 2013.

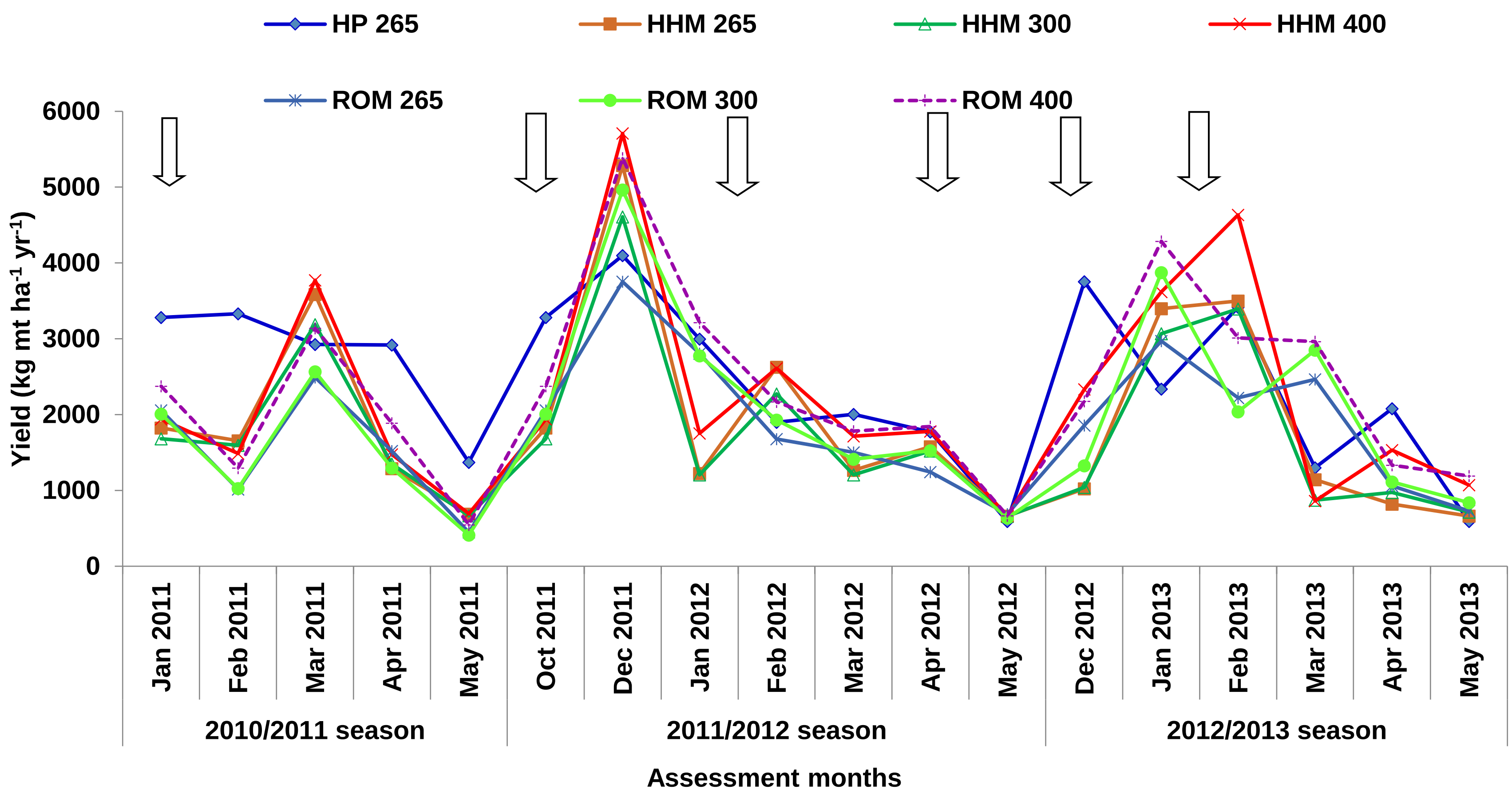



**Figure 6. 4 Monthly yield trends for the different harvesting methods in the 2010/2011, 2011/2012 and 2012/2013 seasons. Arrows indicate the fertilizer application dates**

### 6.4.2 Leaf nitrogen concentration

Leaf N concentration did not differ significantly between harvesting methods during the 2010/2011, 2011/2012 and 2012/2013 seasons ($p<0.05$) (Figure 6.5). There was, however, a trend which showed high variation in leaf N concentration in each treatment. Although not statistically significant, there was a tendency in the 2012/2013 season for the leaf N concentration to increase with increasing N fertilizer application (Figure 6.5C). The highest leaf N concentration was recorded from bushes receiving 300 (3.9%) and 400 kg N $ha^{-1}$ $yr^{-1}$ (4.4%) and harvested with the ride-on machine. The lowest leaf N concentration (2.9%) was recorded in bushes receiving 265 kg N $ha^{-1}$ $yr^{-1}$ and harvested with HHM and ROM (2.9%). This is below the critical N level for tea of between 3.5-4.5% (Drinnan, 2008).

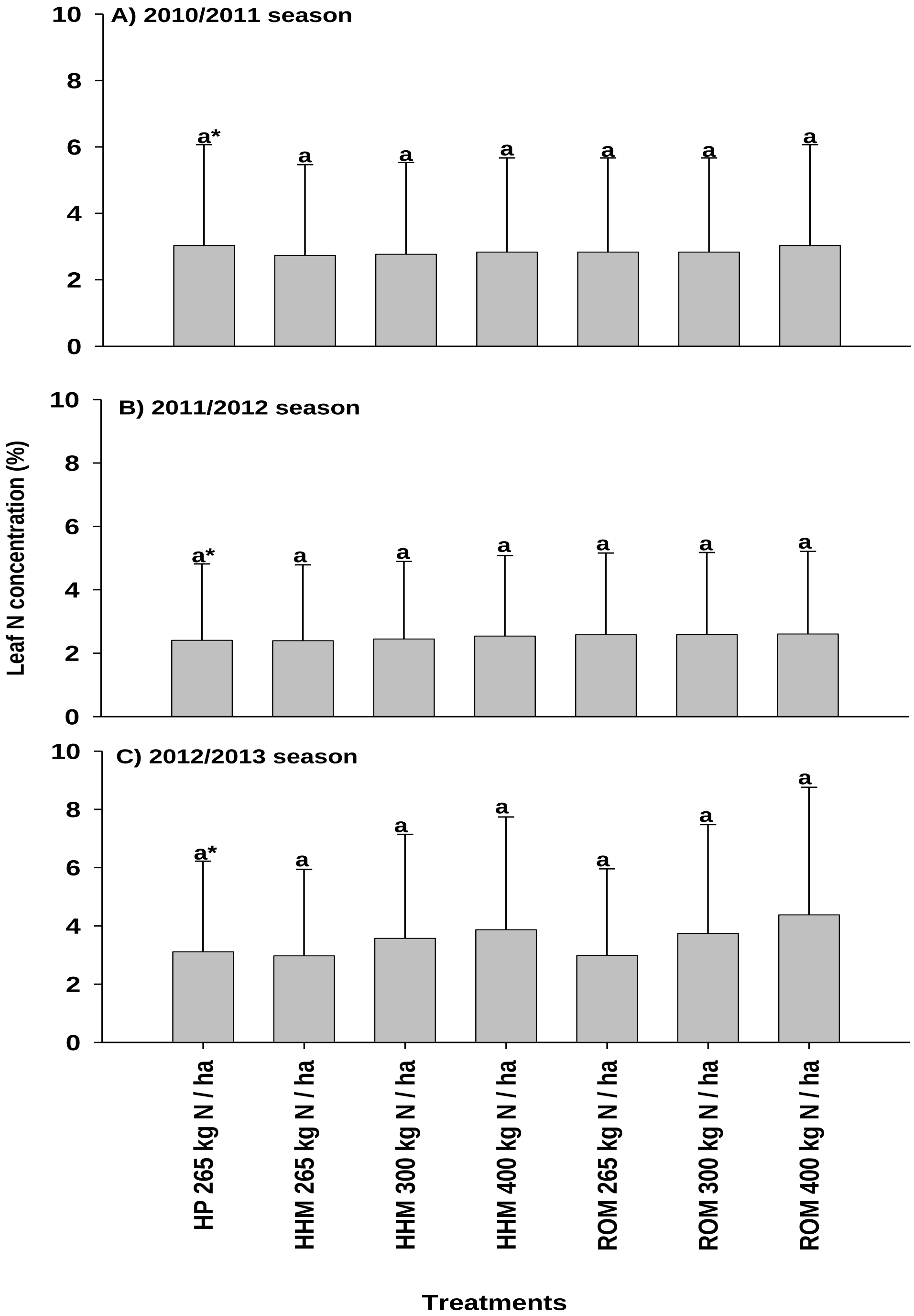



**Figure 6. 5 Leaf nitrogen concentration in the third leaf of a PC 108 shoot, as affected by different treatments during the 2010/2011, 2011/2012, and 2012/2013 growing seasons**

***Means followed by the same letter within the same season are not significantly different from each other at p<0.05 Duncan's Multiple Range Test (DMRT)**

### 6.4.3 Green leaf quality

When % good leaf quality data was combined for the three years and three fertilizer treatments, there was no significant ($p > 0.05$) interaction for % green leaf (Table 6.2). There was, however, a significant ($p < 0.05$) (year x harvesting method) interaction for % good leaf quality when considering harvesting methods (Table 6.2). The year x harvesting methods interaction shows a generally similar % good leaf ranking of harvesting method treatments for each year. This shows that the interaction was caused primarily by the magnitude of % good leaf quality differences between the years. However, there was no significant ($p > 0.05$) year x fertilizer interaction effect on % good leaf quality.

**Table 6.2 Degrees of freedom, mean squares, and F probabilities for the combined analysis of variance for yield, harvesting methods and fertilizer rates at Tingamira Estate, Chipinge, Zimbabwe from 2011 to 2013.**

| Source of variation | df† | Mean square Good leaf quality (%) |
|---|---|---|
| Harvesting method (HP vs MH) | 1 | 329.754** |
| HP vs HHM vs ROM | 1 | 0.579 NS |
| Fertilizer rates | 2 | 0.212 NS |
| Harvesting method vs fertilizer rate | 2 | 3.984 NS |
| **Error (a)** | **12** | **4.541** |
| year | 2 | 41.857** |
| Year x harvesting method (HP vs MH) | 2 | 32.699** |
| Year x HP vs HHM vs ROM | 2 | 16.715* |
| Year x fertilizer rates | 4 | 1.045 NS |
| Year x harvesting method vs fertilizer rate | 4 | 1.276 NS |
| **Error (b)** | **28** | **1.998** |

*** Significant at the 0.05 level of probability.**
**** Significant at the 0.001 level of probability.**
**NS - Not significant**
**† df, degrees of freedom.**

Generally % good leaf quality was higher during the 2010/2011 growing season than 2011/2012 and 2012/2013, with the lowest % green leaf quality recorded in the

2011/2012 season (Figure 6.6), although not significant different. However, within each season there were no significant % good leaf quality differences between the different N-application rates.

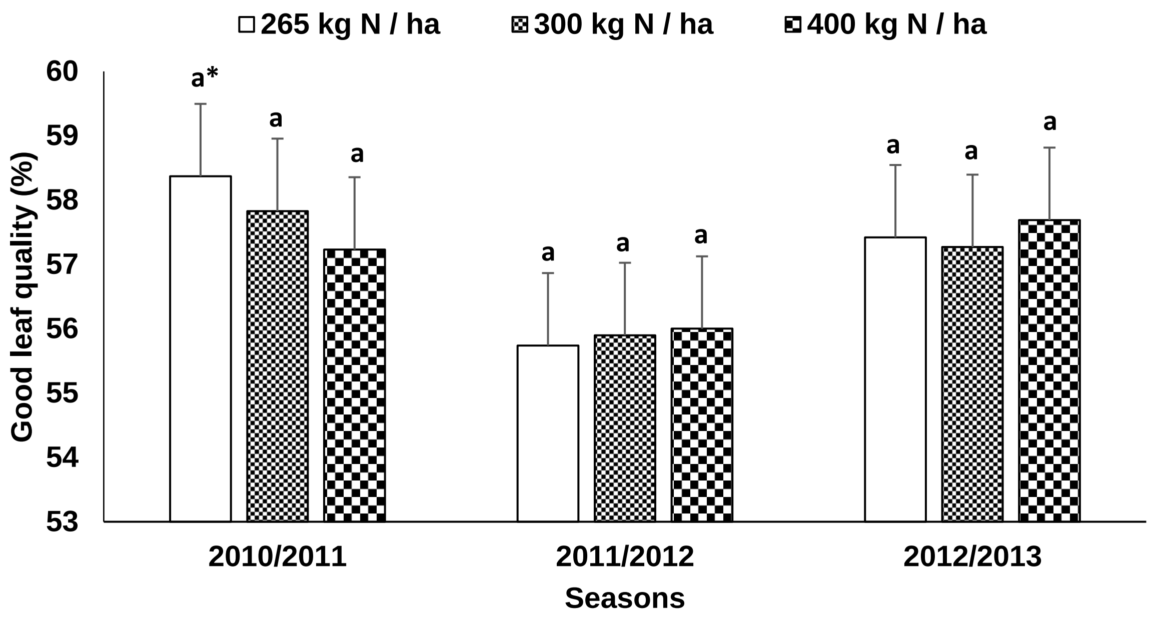



**Figure 6. 6 Effect of increasing N-application rate on good leaf quality (%) under machine harvesting across the different harvesting seasons (p<0.05)**

***Means followed by the same letter in the same year are not significantly different from each other at p<0.05 Duncan's Multiple Range Test (DMRT)**

Hand plucking produced a significantly higher (p <0.05) % good leaf quality compared with machine harvesting techniques, at all N-application rates, during the 2010/2011 and 2011/2012 seasons (Figure 6.7). However, in the 2012/2013 season only the ROM 300 kg N $ha^{-1}$ $yr^{-1}$ treatment had % good leaf quality which was significantly lower than the hand plucked bushes. Increasing the N-application rate in the HHM and ROM plots to 400 kg N $ha^{-1}$ $yr^{-1}$, brought % good leaf quality levels similar to the HP treatments in the 2011/12 and 2012/2013 seasons (Figure 6.7).

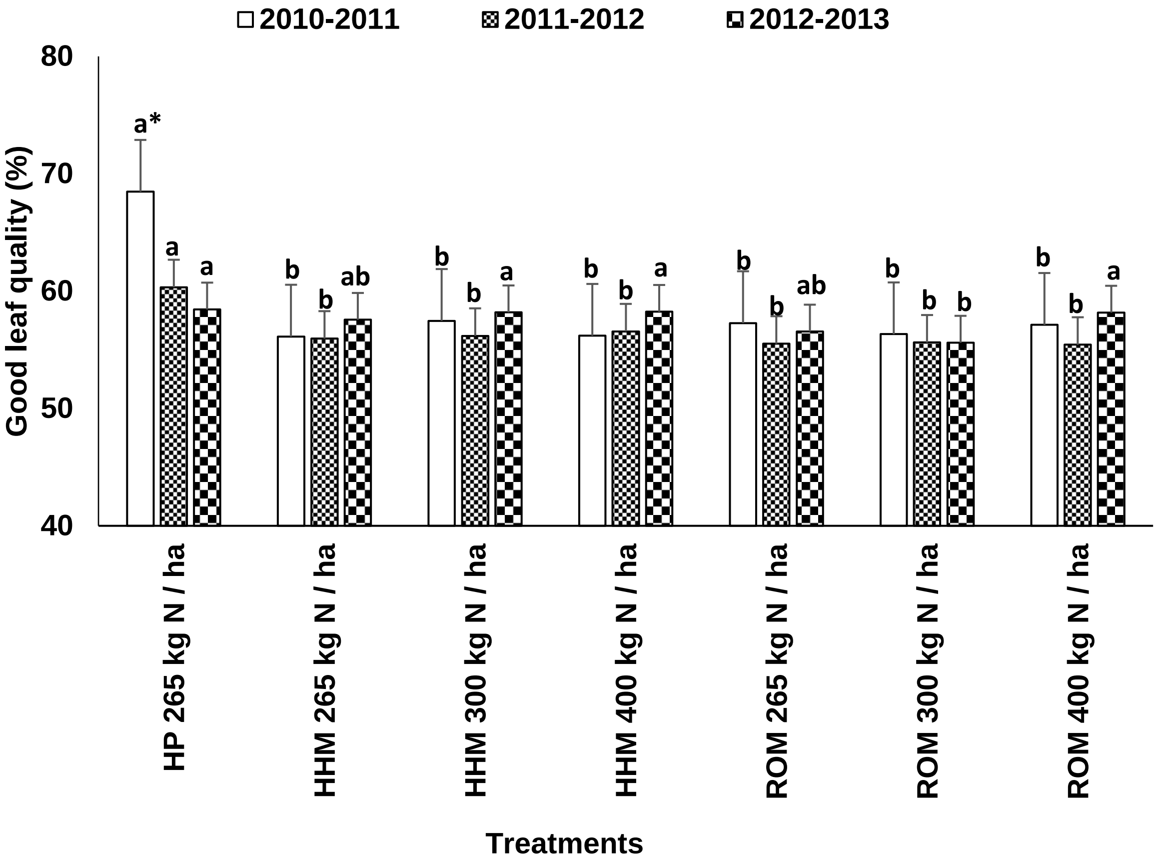



**Figure 6. 7 Effect of harvesting method and increasing nitrogen application rate on green leaf quality over the three seasons of the study (% good leaf)**
**HP= Hand plucking, HHM= Hand held machine, ROM= Ride on machine**
***Means followed by the same letter in the same year/ season are not significantly different from each other at $p<0.05$. Duncan's Multiple Range Test (DMRT)**

### 6.4.4 Nitrate concentration of the leachate in the soil

The concentration of nitrate in the leachate collected from the WFDs installed 0.20 m below the soil surface varied across years, and did not show any consistent pattern (Figure 6.8). However, the nitrate leaching incidents were related to fertilizer application timing and high rainfall events. In the 2010/2011 season, nitrate concentration of the leachate from the active root zone was higher under the high fertilizer rates, that is, ROM 300 and 400 kg N $ha^{-1}$ $yr^{-1}$ (Figure 6.8A). The highest nitrate concentrations in this season were observed in January (117 mg $L^{-1}$) and April (183 mg $L^{-1}$) in the ROM treatment receiving 400 kg N $ha^{-1}$ $yr^{-1}$. These high concentrations followed 41 days after fertilizer applications on 27 November 2010. January 2011 was generally a wet month, with a total of 498 mm rainfall. In April 2011 nitrate leachate readings were taken 51 days after the third fertilizer application (18 February 2011) and four days after receiving 36 mm of rainfall. The low levels of nitrate recorded in the bushes harvested by hand plucking could mean rapid uptake by the shoots and harvested as yield.

Similar to the 2010/2011 growing season, the nitrate leaching events for the 2011/2012 growing season were also linked to fertilizer applications, followed by rainfall events. However, in contrast to the previous season, higher nitrate levels were consistently recorded in the hand plucked treatments compared to the machine harvesting treatments at the 0.20 m soil depth. Generally nitrate levels from all treatments were low in February and this was most probably because rainfall was low during this month (Fig. 6.8B).

In the 2012/2013 season less than 50 mg $L^{-1}$ nitrate was recorded in all treatments (Figure 6.8C), which was possibly as a result of the low rainfall experienced during the year (Figure 6.1). Nitrate levels were marginally higher in hand plucked treatments as opposed to the machine harvesting treatments, with the highest concentration under HP being recorded in December, following the second fertilizer application (Figure 6.8C).

The WFDs installed at 0.60 m soil depth had very few response events (six times in 2011/2012 and six times in 2012/2013). As at the 0.2 m depth, the concentration of nitrate in the leachate collected at 0.60 m soil depth differed between the two seasons studied and was not consistent (Figure 6.9). During the 2011/2012 season the concentration of nitrate in leachate collected from the HHM 265 kg N $ha^{-1}$ $yr^{-1}$ treatment was highest (ranging from 20 mg $L^{-1}$ in November 2011 to 83 mg $L^{-1}$ in December 2011). No nitrate was recorded in any of the other treatments during this season (Figure 6.9A). Similarly, during the 2012/2013 growing season, high rates of nitrate in the leachate were recorded under HHM 265 kg N $ha^{-1}$ $yr^{-1}$ for the first three WFD responses. However, in contrast to the previous season nitrate was recorded in the soil solution from the HHM and ROM treatments receiving 400 kg N $ha^{-1}$ $yr^{-1}$ in the last three WFD response events (Figure 6.9B).

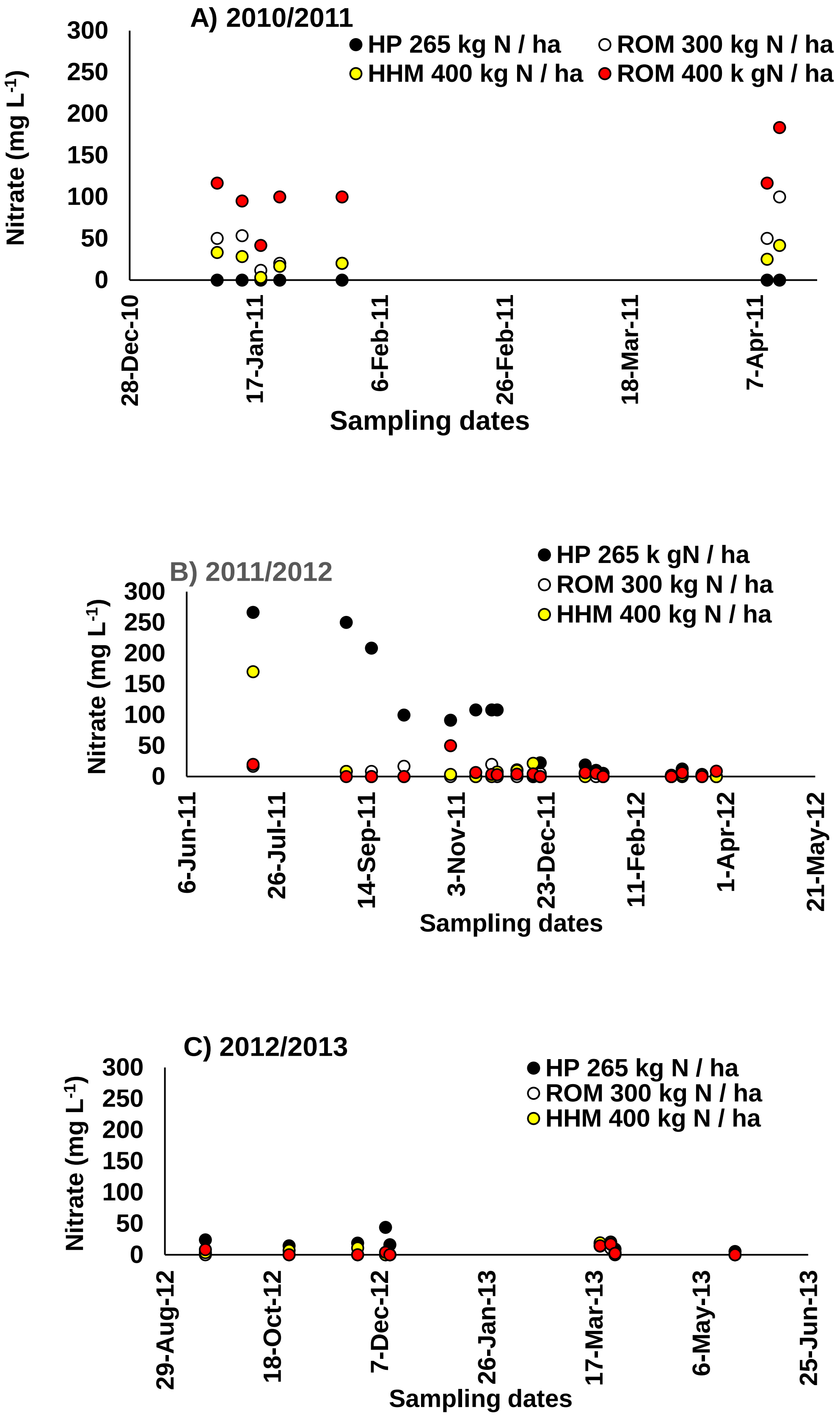
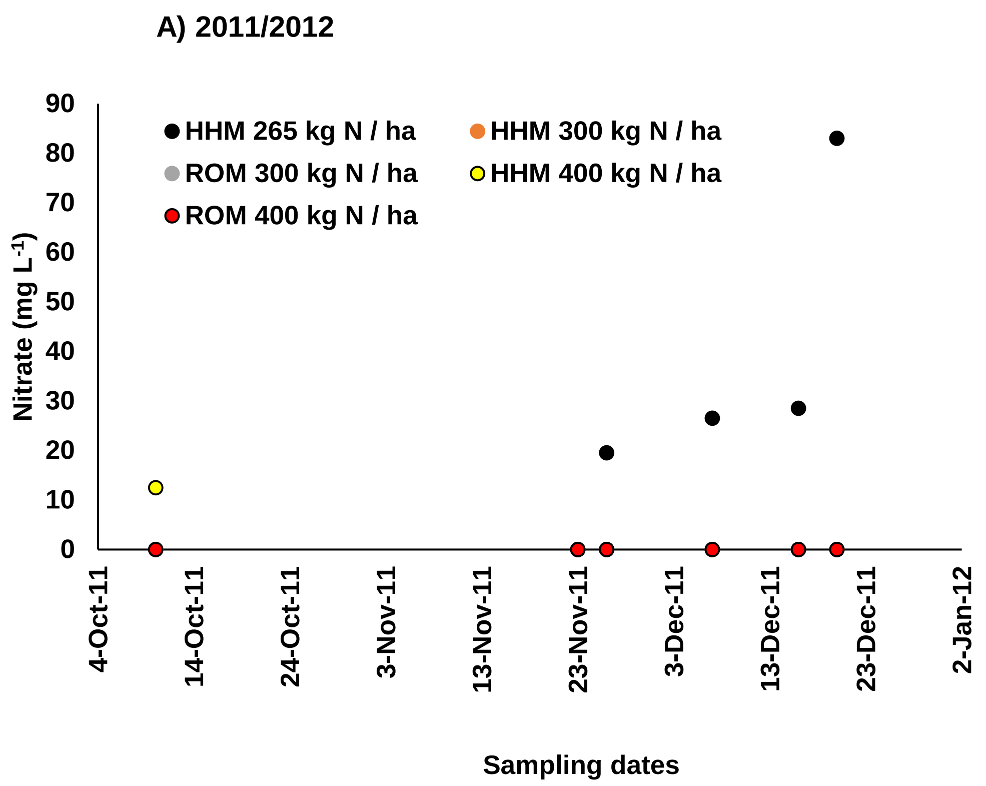



**Figure 6. 8 Nitrate concentration in the leachate recorded at 0.2 m depth in treatments which received 265, 300 and 400 kg N ha$^{-1}$ yr$^{-1}$ during the (A) 2010/2011, (B) 2011/2012 and (C) 2012/2013 seasons.**



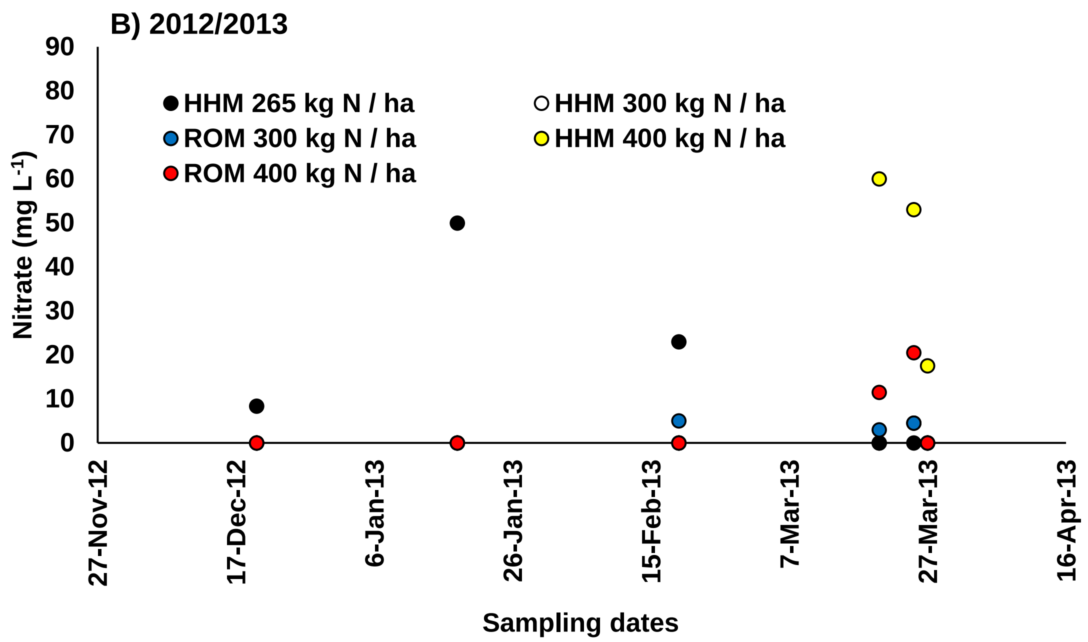




**Figure 6. 9 Nitrate concentration in the leachate recorded at 0.6 m depth in machine harvesting treatments which received 265, 300 and 400 kg N ha$^{-1}$ yr$^{-1}$ during the (A) 2011/2012 and (B) 2012/2013 seasons.**

### 6.4.5 Residual inorganic nitrogen

Generally, residual inorganic N varied significantly ($p<0.05$) among treatments, across years and soil depths (Table 6.3). With the exception of the 2010/2011 growing season, mean residual inorganic N increased, although not significantly, as the fertilizer application rate increased, at both the 0-0.2 and 0.2-0.4 m soil layers. Mean residual inorganic N was lowest in the first season after pruning, in the 2010/2011 growing season, as compared with the second (2011/2012) and third (2012/2013) seasons. In the 2010/2011 season, significantly higher ($p<0.05$) mean residual inorganic N (10.5 mg $kg^{-1}$) was found in the HP 265 kg N $ha^{-1}$ $yr^{-1}$ treatment than in the ROM 265 kg N $ha^{-1}$ $yr^{-1}$ (6.4 mg $kg^{-1}$) treatment in the top 0.2 m layer (Table 6.3A).

During the 2011/2012 season, mean residual inorganic N in the lower 0.2-0.4 m soil layer was significantly higher in the ROM 400 kg N $ha^{-1}$ $yr^{-1}$ treatment than in the hand plucked treatment (Table 6.3B). In addition, soil residual inorganic N was significantly lower in the HHM treatments receiving 265 and 300 kg N $ha^{-1}$ $yr^{-1}$ than in the hand plucked treatment in the 2011/2012 season. In the 2012/13 growing season, no machine harvesting treatment was significantly different from the control at both depths.

**Table 6.3 Mean available inorganic N in the A) top 0 – 20 cm and B) 20 – 40 cm soil layers at the end of the 2010/2011, 2011/2012 and 2012/2013 growing seasons.**

| Treatments | Mean Residual Inorganic N (mg kg$^{-1}$) | | |
|---|---|---|---|
| | 2010/2011 season | 2011/2012 season | 2012/2013 season |
| **A. Top 0 – 0.20 m soil depth** | | | |
| HP 265 kg N ha$^{-1}$ | 10.5**a** | 27.1**ab** | 24.0**a*** |
| HHM 265 kg N ha$^{-1}$ | 7.4**ab** | 18.1**b** | 16.8**a** |
| HHM 300 kg N ha$^{-1}$ | 8.7**ab** | 32.7**a** | 25.0**a** |
| HHM 400 kg N ha$^{-1}$ | 9.7**ab** | 37.3**a** | 26.0**a** |
| ROM 265 kg N ha$^{-1}$ | 6.4**b** | 24.3**ab** | 21.8**a** |
| ROM 300 kg N ha$^{-1}$ | 9.7**ab** | 26.1**ab** | 23.7**a** |
| ROM 400 kg N ha$^{-1}$ | 8.5**ab** | 34.5**a** | 21.6**a** |
| **LSD** | **13.57** | **18.40** | **NS** |
| **CV** | **15.00** | **18.50** | **22.90** |
| **SED** | **3.31** | **13.06** | **13.06** |
| **B. 0.20 – 0.40 m soil depth** | | | |
| HP 265 kg N ha$^{-1}$ | 10.6**ab** | 24.3a | 22.8**ab** |
| HHM 265 kg N ha$^{-1}$ | 8.7**b** | 11.2**c** | 14.3**b** |
| HHM 300 kg N ha$^{-1}$ | 9.8**ab** | 11.2**c** | 16.5**ab** |
| HHM 400 kg N ha$^{-1}$ | 10.9**ab** | 18.7**bc** | 19.1**ab** |
| ROM 265 kg N ha$^{-1}$ | 8.8**ab** | 26.1**ab** | 21.9**ab** |
| ROM 300 kg N ha$^{-1}$ | 8.9**ab** | 33.6**ab** | 28.0**a** |
| ROM 400 kg N ha$^{-1}$ | 11.6**a** | 37.4**a** | 28.4**a** |
| **LSD** | **12.61** | **29.35** | **19.62** |
| **CV** | **23.40** | **14.30** | **36.90** |
| **SED** | **2.83** | **13.03** | **9.34** |

***Means followed by the same letter in the same column are not significantly different from each other at P<0.05 Duncan's Multiple Range Test (DMRT)**

### 6.4.6 Cost analysis

The additional fertilizer cost as a result of increasing the N application rate from 265 to 300 kg N $ha^{-1}$ was \$27.30, whilst it cost an additional \$105.30 to increase N from 265 to 400 kg N $ha^{-1}$ $yr^{-1}$. This was constant for all seasons (Table 6.4).

**Table 6. 4 Cost implications of increasing the N application rate under machine harvesting treatments during the 2010/2011, 2011/2012 and 2012/2013 seasons in comparison to hand plucking at 265 kg N $ha^{-1}$ $yr^{-1}$**

| Season | Harvesting method | Additional Fertilizer cost (\$$ha^{-1}$) | Income (\$ $ha^{-1}$) | Return per \$ invested $ha^{-1}$ |
|---|---|---|---|---|
| **2010/2011** | **HHM 300 kg N $ha^{-1}$** | 27.30 | -145.00 | -5.30 |
| | **HHM 400 kg N $ha^{-1}$** | 105.30 | 83.00 | 0.79 |
| | **ROM 300 kg N $ha^{-1}$** | 27.30 | -57.00 | -2.00 |
| | **ROM 400 kg N $ha^{-1}$** | 105.30 | 443.00 | 4.20 |
| **2011/2012** | **HHM 300 kg N $ha^{-1}$** | 27.30 | -338.00 | -12.40 |
| | **HHM 400 kg N $ha^{-1}$** | 105.30 | 439.00 | 4.16 |
| | **ROM 300 kg N $ha^{-1}$** | 27.30 | 387.00 | 14.00 |
| | **ROM 400 kg N $ha^{-1}$** | 105.30 | 951.00 | 9.00 |
| **2012/2013** | **HHM 300 kg N $ha^{-1}$** | 27.30 | 123.00 | -4.50 |
| | **HHM 400 kg N $ha^{-1}$** | 105.30 | 905.00 | 8.60 |
| | **ROM 300 kg N $ha^{-1}$** | 27.30 | 190.00 | 7.00 |
| | **ROM 400 kg N $ha^{-1}$** | 105.30 | 754.00 | 7.20 |
| **Across Seasons** | **HHM 300 kg N $ha^{-1}$** | **27.30** | **-607.20** | **-22.20** |
| | **HHM 400 kg N $ha^{-1}$** | **105.30** | **1427.00** | **13.50** |
| | **ROM 300 kg N $ha^{-1}$** | **27.30** | **527.00** | **19.30** |
| | **ROM 400 kg N $ha^{-1}$** | **105.30** | **2345.00** | **22.30** |

Increasing the N-application rate from 265 to 400 kg N $ha^{-1}$ $yr^{-1}$ resulted in increased income and return per dollar invested per ha in all three seasons. However, only increasing the N-application rate from 265 to 300 kg N $ha^{-1}$ $yr^{-1}$ under HHM resulted in a loss of income and return per dollar invested in all three seasons. Whilst there was a loss in income in the first season (2010/2011) when N-application rate was increased from 265 to 300 kg N $ha^{-1}$ $yr^{-1}$ in bushes harvested by ride-on machines, this was reversed in the following two seasons as yields increased**.**

Across the three study years, HHM and ROM treatments receiving 400 kg N ha$^{-1}$ yr$^{-1}$ produced the greatest income ($1427 and $2345, respectively), although HHM 400 kg N ha$^{-1}$ yr$^{-1}$ produced a lower return per dollar invested ($13.50) compared to ROM receiving 400 kg N ha$^{-1}$ yr$^{-1}$ ($22.30) and 300 kg N ha$^{-1}$ yr$^{-1}$ ($19.30) and HHM receiving 300 kg N ha$^{-1}$ yr$^{-1}$ ($26.20). Whilst a lower income was realized at 300 kg N ha$^{-1}$ yr$^{-1}$, the return per dollar invested was higher.

## 6.5 Discussion

Previous studies from Malawi and Pakistan on clonal teas reported that high nitrogen levels enhance shoot growth (Malenga, 1997, Hamid, *et al.*, 2002). Other studies by Drinnan (2008) also showed that higher N-application rates increased tea yield under machine harvesting, although other authors suggest tea quality may be compromised by higher N application rates (Owuor and Odhiambo, 1994, Chen, *et al.*, 2015). It was therefore hypothesized that higher N-application rates could mitigate the decline in tea yield previously reported in continuously mechanically harvested tea bushes, but if not managed carefully higher N-application rate could lead to increased leaching losses and poorer quality tea.

Generally, increasing the rate of N applied to machine harvested (HHM and ROM) bushes from 265 to 400 kg N ha$^{-1}$ yr$^{-1}$ increased yields to levels similar or higher than hand plucked bushes. It should however be noted that the additional N applied to increase yield was a blend thus the additional nutrients (P, K, B and Zn) in the blend could have also played a role in improving the yields. Yield increases of between 5 and 10% were observed under machine harvesting treatments, which received 400 kg N ha$^{-1}$ yr$^{-1}$, compared to hand plucking, which received the standard rate of 265 kg N ha$^{-1}$ yr$^{-1}$. Similarly, yield increases of between 10 and 21% were observed in mechanically harvested plots when N application rates were increased from 265 to 400 kg N ha$^{-1}$ yr$^{-1}$. This increment in tea yield with increased N-application rate is in agreement with previous findings by Cheruiyot, *et al.*, (2010). This is because sufficient N fertilization is needed to maintain favourable growth and good yield, when soil water and air temperatures are non-limiting (Cheruiyot, *et al.*, 2010). This is particularly important due to the high N removal rate (4% in leaves) at harvest of tea. Nitrogen concentration in leaves from the ROM 300 and ROM 400 kg N ha$^{-1}$ yr$^{-1}$ treatments accounted for 3.9 – 4.4% by mass, which is within the critical foliar N ranges of 3.5 to

4.5 reported by Drinnan (2008). However, HHM, ROM and HP treatments at 265 kg N $ha^{-1}$ $yr^{-1}$ recorded leaf N of 2.9%, which is below the critical foliar levels for N for tea (Drinnan, 2008), indicating that these bushes could be N limited. This could be as a result of insufficient N uptake due to the low plant available N, which was also indicated by low soil residual N in the 0-0.20 m soil layer.

Increasing N fertilizer application rates from 265 kg to 300 kg $ha^{-1}$ $yr^{-1}$ did not improve tea yield significantly, indicating that the extra 35 kg N added was insufficient to increase yield. Low income, and in some years negative return per dollar invested, was realized throughout the study period. The significant tea yield increment observed as the fertilizer rate increased to 400 kg N $ha^{-1}$ $yr^{-1}$ indicates the extra 135 kg N $ha^{-1}$ $yr^{-1}$ contributed to the increased tea yield, income and return per dollar invested. This is supported by the low nitrate leaching (2010/2011) and low residual inorganic N, indicating the nitrogen was used by the tea plants for biomass production.

Over the 3 year study period, higher % good leaf quality was produced under HP compared to machine harvesting treatments. Larger percentages of the finer fractions, as compared to the coarser fractions, contributed to the higher % good leaf quality under HP in the first two seasons. However, in the third season there was no difference between the harvesting methods, except ROM 300 kg N $ha^{-1}$ $yr^{-1}$ which had the lowest % good leaf quality, showing an improvement in % good leaf quality. Mukumbarezah (2001) also reported an improvement in green leaf quality in the second and third years of mechanically harvested tea in Zimbabwe. As the machines and tea bushes get accustomed to each other there should be no drop in quality. This is supported by Nandagopalan*, et al.* (2014), who reported that mechanical harvesting over several years changes the plucking table, allowing only younger tender shoots to emerge out of the plucking table and keeping mother leaf uniformly in a plain horizontal level, thereby allowing the harvesting of only the tender shoots and leaving the maintenance layer intact. Since mechanical harvesting can cover a hectare in a short period of time all fields on the estate will be plucked on time, without any missed rounds, so the possiblity of overgrown shoots due to missed rounds, or rounds that are behind schedule, is reduced, such that the overall quality will actually improve.

In order to increase % good leaf quality under machine harvesting so that it is comparable to that of HP, N-application rate was increased from 265 to 400 kg N $ha^{-1}$

$yr^{-1}$ in machine harvested plots in an attempt to increase yields to levels similar to hand plucked controls. It was also hoped that this treatment would also increase % good leaf quality to levels similar or above HP. However, the increase in yield was not accompanied by an increase in % green leaf quality, except in the 2012/2013 when similar % green quality was achieved in all treatments.

Although high N-application rates were shown to improve yield, the possibility of excessive nitrate leaching below the active root zone is considered a potential threat to ground water and is an economic loss to the grower. However, nitrate leaching from high N-application treatments of ROM and HHM both at 400 kg N $ha^{-1}$ $yr^{-1}$ remained lower or similar to the standard rate of 265 kg N $ha^{-1}$ $yr^{-1}$ (HP 265 kg N $ha^{-1}$ $yr^{-1}$). The only exception was the first year (2010/2011) after pruning, where nitrate leaching from ROM 400 kg N $ha^{-1}$ $yr^{-1}$ remained higher than the other treatments. The 2010/2011 season was characterized by a higher number and intensity of rainfall events than the other seasons. In 2010/2011 there were ten such events, with a total annual rainfall of 1306 mm, as compared to six and eight rainfall events in the 2011/2012 and 2012/2012 seasons, with total annual rainfall of 883 and 1092 mm respectively. Seasonal yield trends showed that in order to increase yield further, more frequent N applications should possibly target the periods of low yields, depending on rainfall distribution. Residual nitrate-N was lowest during 2010/2011 for all treatments, compared with the other years, indicating that the cause for the high nitrate leaching losses in this season was mainly intensive rainfall events. The other possible reason for the high nitrate leaching during the first year of 2010/2011 is the additional N released from the pruning, which decreased in the second and third years after pruning. Thus, the potential for nitrogen leaching during the first year after pruning could be minimized by quantifying the amount of N that can be mineralized during the first year and adjust the N fertilizer application rate accordingly. It is therefore important to consider splitting the fertilizer applications further, so that little is applied but more frequently to reduce leaching losses under high rainfall events and also to target periods of lower shoot growth, thereby increasing yield. The study showed that this is possible because high yields followed fertilizer application and rainfall events and favourable temperatures.

High N-application rates pose a risk that the high cost of the fertilizer will not be offset by improved yields and higher returns, however, this study showed that higher income and return per dollar invested was realized under machine harvesting at these high N rates. In all the three seasons HHM and ROM 400 kg N $ha^{-1}$ $yr^{-1}$ had the greatest income, although in 2011/2012 season the return per dollar was less than the 300 kg N $ha^{-1}$ $yr^{-1}$. This could be due to the lower yields obtained as a result of the poor rains received in this season. These studies however, did not take into account a detailed analysis of the cost of machine or the labour in coming up with the calculations on income and return per dollar invested. A detailed cost benefit analysis should be performed in future.

**6.6 Conclusions**

Increasing N application rates to 400 kg N $ha^{-1}$ $yr^{-1}$ under machine harvesting (HHM and ROM) improved tea yield of these plots, making them comparable to or even higher than HP, which received the standard fertilizer application rates of 265 kg $ha^{-1}$ $yr^{-1}$. Green leaf quality from the high N application rates of 400 kg N $ha^{-1}$ $yr^{-1}$, however, remained less or equal to that of HP which received the standard application rates. The study also showed that concentration of nitrate in the leachate collected at 0.20 and 0.60 m soil depths from the high N application rates did not exceed that of the standard N application rates in all but the first year. It was apparent that the highest income and return per dollar invested was realized under HHM and ROM at 400 kg N $ha^{-1}$ $yr^{-1}$. Therefore, increasing fertilizer rates from 265 to 400 kg $ha^{-1}$ $yr^{-1}$: a) will improve tea yield and b) will not cause significant nitrate leaching losses under mechanical harvesting. However, increasing fertilizer rates to 400 kg $ha^{-1}$ $yr^{-1}$ will not improve green leaf quality equal to that of hand plucking. Therefore the hypothesis that increasing N-application rate will mitigate against yield decline is accepted, but increasing N – application will not increase % green leaf quality and hence it is rejected.

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# CHAPTER 7

# General conclusions and recommendations

## 7.1 Overview of the study

Hand plucking is throughout the world believed to be the best method of tea harvesting and has evolved with the industry to improve the productivity and quality of tea. The most desirable shoots for plucking are 42 day-old shoots, as these shoots represent the best compromise between yield and quality (TPH, 1990). However, numerous shoot generations are present on a tea bush at any one time and the most successful harvesting strategies are those that selectively harvest these 42 day-old shoots. The flexibility of plucking round lengths and selectivity of hand pluckers have therefore most often resulted in high yields of good quality. However, since the early 1990s the number of available pluckers for harvesting has declined, whilst the cost of labour has increased. Therefore, it has become increasingly necessary to mechanize tea harvesting on the large tea estates, not only to increase the productivity of the workers, but also to reduce the cost of production (Nandagopalan*, et al.*, 2014). A decline in yield and quality was, however, observed with mechanical harvesting of tea, which posed great challenges to tea industries in central and southern Africa. It was against this background that this study was undertaken at Tingamira estate, in Chipinge, Zimbabwe to investigate the possible causes of yield and quality decline under continuous mechanical harvesting of tea and possible mitigating actions to prevent this decline. Previous studies in Malawi, Kenya and Zimbabwe (Bore, 1997, Nyasulu, 2006, Madamombe, 2008) attributed the decline in quality in mechanically harvested tea to a higher percentage of undesirable shoots under machine harvesting, whilst Wijeratne (2003) attributed yield decline to the harvesting of higher percentage of immature shoots, due to the non-selectivity of machine harvesting. As the harvesting method affects the number, size and type of shoots remaining on the tea bush (Burgess*, et al.*, 2006), the partitioning and utilization of assimilates is also expected to be impacted by the plucking policy (Wijeratne, 2003). It was therefore hypothesized that the indiscriminate removal of both young and older shoots from the plucking table would alter the radiation interception dynamics of the bushes and sink/source relationships within the canopy. This in turn would impact plant photosynthesis within the canopy, which ultimately impacts tea bush productivity and as a result tea quality.

As mechanical harvesting cannot be avoided on many estates, it is important to find a strategy that will, at the very least, limit the decline in yield and quality previously reported in mechanically harvested tea. The indiscriminate harvesting of young shoots, which contain the greatest concentration of nitrogen (Dang, 2005, Kamau*, et al.*, 2008), could affect the nitrogen dynamics within the tea bush. A nitrogen fertilization strategy specific for mechanically harvested tea may therefore help prevent the observed yield decline. This is because nitrogen has been shown to be markedly and positively correlated with shoot growth (Hamid*, et al.*, 2014, 2002) and therefore yield in tea (Cheruiyot*, et al.*, 2010, Chen*, et al.*, 2015) and fertilizer norms have been predominantly designed for hand plucked bushes. Therefore, it was postulated that increasing nitrogen application could mitigate against yield and quality decline observed under continuous mechanical harvesting of tea. In this study two machines were used, i.e. a hand-held machine and a ride-on machine and compared with standard hand plucking.

## 7.2 Yield decline in mechanically harvested clonal tea (*Camellia sinensis* (L) O. Kuntze) as influenced by changes in source/sink and radiation interception dynamics in the canopy

In tea cultivation, canopy depth or the amount of leaves is artificially controlled by plucking. According to Okano*, et al.* (1995), the removal of immature or mature shoots from the plucking table has a profound effect on canopy photosynthesis and dry matter accumulation. This effect is likely to be exacerbated under mechanical harvesting due to the indiscriminate nature of the machines. This three year study confirmed an overall yield reduction of between 17 and 19% under mechanical harvesting of tea compared to hand plucking with any additional N. This reduction in yield was associated with a decline in both yield components of tea, which included the number of shoots per unit area and the mean mass of these shoots. This yield reduction was attributed to an alteration in canopy architecture caused by the indiscriminate harvesting method of the machines, as compared to hand plucked bushes. This resulted in a decrease in interception of photosynthetically active radiation in the top 10 cm of the canopy, indicating a depleted maintenance layer. As the maintenance layer (source) is suggested to provide the assimilates for the developing shoots (sinks) (Manivel and Hussain, 1982a, De Costa*, et al.*, 2007), the depletion of this layer resulted in a reduced photosynthetic capacity of the bush, which resulted in these bushes being source limited. Shoot growth was also affected in these bushes due to the presence of larger numbers of immature shoots (buds and 1+b) (56%), as compared to hand plucked bushes (30%). As these shoots are strong sinks, (Magambo and Cannell, 1981, Manivel and Hussain, 1982b, De Costa, *et al.*, 2007), it resulted in increased competition between developing shoots for an already depleted assimilate supply. The growth of these shoots was subsequently retarded, resulting in fewer desirable shoots of lower mass during each season. Shoot composition analysis from mechanically harvested treatments indicated that only 30-35% of the total shoots harvested comprised only 2+b and 3+b of the most desirable shoots as compared to hand plucked bushes, where these desirable shoots made up 46% of the total harvest (Chapter 4). Although yields were significantly lower in the mechanically harvested treatments over the three seasons of measurements, an analysis of the seasonal yield trends revealed periods of higher yields under mechanically harvested treatments compared to hand plucking. The high yields were associated with periods of increased moisture (rainy season), allowing the dormant buds to break producing peaks in harvestable shoots, which are commonly known as the "Fordham peaks". These peaks alternate with periods of lower yields (troughs) which are associated with low moisture and absence of pluckable shoots (TPH, 1990). The peak in yield as a result of the synchronization of shoot growth is exacerbated in bushes which are mechanically harvested, as all shoots above the plucking table are removed, irrespective of size. This leads to a smaller number of shoot generations on the tea bushes, which accounts for the greater number of peaks and troughs in yield under mechanical harvesting, as compared to the much more selective hand plucking.

## 7.2 The impact of continuous mechanical harvesting of tea (*Camellia sinensis* (L) O. Kuntze) and increasing N-application rate on black tea quality parameters

In addition to a decline in yield under mechanical harvesting, there is also a general perception that the quality of the tea declines, as a result of mechanical injury to the leaves and the non-selective nature of shoot plucking under machine harvesting. This is important as the quality of the plucked leaf and black tea quality will ultimately determine the price and marketability of the tea. The indiscriminate harvesting of tea by the machines in this study resulted in a higher percentage of immature shoots, one and a bud, two and a bud shoots, overgrown shoots, hard banjhi, half cut leaf, three quarter cut leaf and broken pieces of stem and leaf than in hand plucked bushes (Chapter 4), which ultimately brought down the % good leaf in the first two seasons following pruning from 57% to 56% under machine harvesting, compared to 69% and 60% under hand plucking (Chapter 5). This 1% decline in good leaf quality under machine harvesting is significant when total yields are considered. However, in the third season the % good leaf quality in almost all the machine harvested plots was equal to hand plucking, and was therefore more a direct effect of the machine. After two years of continuous mechanical harvesting, the tea bushes seem to have adapted to machine harvesting. This agrees with studies done by Nandagopalan*, et al.* (2014), who showed that quality deterioration under continuous mechanical harvesting normalizes with time and the adverse impact on bush physiology and productivity is reduced. According to Mukumbarezah (2001), % good leaf below 60% should be considered unacceptable. Whereas some estates such as Sayama estate in Malawi consider anything below 70% good leaf quality under mechanical harvesting as unacceptable (*pers comm*, Chris Lewis, Estate Manager, January 2014, Sayama Estate, Malawi).

The higher percentage of undesirable shoots, especially the half cut and three quarter cut leaves and broken pieces of stem and leaf, under continuous mechanical harvesting as a result of the lack of selectivity under mechanical harvesting (Chapter 4) is expected to accelerate chemical processes, such as field fermentation before the actual manufacturing process starts in the factory, which is believed to reduce the black tea quality. According to Tanaka*, et al.* (2009), when plant tissues undergo physiological changes, such as fruit ripening or through herbivory (or mechanical harvesting), polyphenols (macromolecules) are chemically converted to secondary polyphenols by enzymatic or non-enzymatic reactions. These reactions involve the conversion of simple catechins into a complex mixture of oxidation products. These polyphenols are most susceptible to oxidation and their reactivity is closely related to plant defense systems in response to oxidative stress (Tanaka*, et al.*, 2009). The higher percentage of the undesirable shoots in mechanically harvested bushes was postulated to negatively impact the organoleptic evaluation of mechanically harvested leaf and reduce the total score of the important black tea quality parameters and valuation.

Tea quality can be defined by the appearance of dry tea, as well as the colour, aroma and taste of tea liquor (Zheng*, et al.*, 2016). In central Africa a good quality tea can generally be described as being plain (without aroma), characterized by coppery red colour of the infused leaf, with its liquor being bright, strong and brisk and taking milk well (TRFCA, 2013a, Wright, 2005). Despite initial concerns, results from this study showed no differences in the liquor colour, liquor strength, briskness, brightness, total score and valuation between hand plucking and mechanical harvesting treatments. In some cases teas from mechanically harvested bushes were valued very similarly to teas from hand plucked bushes, and overall there were no significant differences between hand plucking and machine harvesting treatments in terms of tea valuation. Although there were some differences between hand plucking and machine harvesting treatments in terms of the % fibre content and made tea density, all values fell within the specified limits, as prescribed by the tea industry in Malawi, Zimbabwe and India (Ravichandran and Parthiban, 1998, Jose, 2001b)

In support of the organoleptic assessments, when considering all the markers from the biochemical analysis, there was no difference in the type of tea that resulted from the different harvesting techniques and N-application rates. However, a more detailed analysis of the secondary metabolites specific to tea quality, i.e. dimers and trimers of the catechins, showed that these increased in the mechanically harvested teas and in response to increased N-application rates, relative to hand plucking. Theanine, Epicatechin, Epigallocatechin and Epicatechin gallate levels declined under mechanical harvesting relative to hand plucking, with the levels of Theaflavin, Theaflavin gallate and Theaflavin digallate increasing with mechanical harvesting and N-application rate relative to hand plucking (Chapter 5). However, the levels of Theasinensin F/G and Theasinensin C/E was lower in mechanically harvested treatments in both February and May 2013.

Despite the perceptions that the increased mechanical injury to the leaves and a higher percentage of undesirable shoots would reduce black tea quality in mechanically harvested teas, there was no difference between hand plucking and machine harvesting treatments. This study on PC 108 has shown that mechanical harvesting does not cause a reduction in black tea quality and that increasing N-application rate from 265 to 400 kg N $ha^{-1}$ $yr^{-1}$ does not have an deleterious or advantageous effect on the organoleptic evaluation scores and valuation. However, by increasing the N-application rate there was a tendency for increased concentrations of the dimers and trimers of the catechins, which are positively linked to black tea quality. Mechanical harvesting of tea can therefore be recommended as an alternative to hand plucking in regions which face the same labour problems as Zimbabwe.

### 7.3 Increased nitrogen application mitigates yield decline caused by continuous mechanical harvesting of cultivar tea (*Camellia sinensis* (L) O. Kuntze)

The use of mechanical harvesting machines is a reality for many tea estates, as hand plucking is no longer feasible and therefore tea estates must find ways to reduce the perceived negative effects of mechanical harvesting on tea yield and quality. This study demonstrated that yield decline is a reality in mechanically harvested tea bushes, but quality does not seem to be impacted. Mitigating actions were therefore designed to increase yield, without impacting tea quality. It was decided to increase the N-application rate from the norm of 265 to 400 kg N $ha^{-1}$ $yr^{-1}$ to prevent the yield decline.

The study showed that hand plucking, at N application rate of 265 kg N $ha^{-1}$ $yr^{-1}$, consistently produced higher yield over the three year study period, as compared to machine harvesting treatments at 265 and 300 kg N $ha^{-1}$ $yr^{-1}$. However, at higher N-application rates of 400 kg N $ha^{-1}$ $yr^{-1}$ yield increased to levels comparable to or even higher than HP 265 kg N $ha^{-1}$ $yr^{-1}$ under both the HHM and ROM. The benefits of this increased N application rate were, however, only evident in the third season after pruning, which could potentially indicate that more N was now available for shoot growth and the tea bushes were able to draw the N from the top 0.40 m of the soil. Seasonal yield analysis showed periods of high and low yields over the study period, often referred to as 'Fordham peaks' (TPH, 1990, De Costa*, et al.*, 2007), which were influenced by the timing of fertilizer application and rainfall events. Splitting the total fertilizer for the season into more than just two or three applications, as currently recommended (TPH, 1990) to target periods of low yield could therefore benefit mechanical harvesting. These splits could target the troughs, after the peaks in yield, so as to influence shoot growth and increase the number of shoot generations on bushes at any one time. Four to six splits, as recommended for mechanical harvesting in Australia (Drinnan, 2008), could be beneficial in terms in yield.

The low residual N in the 0-0.20 m and 0.2-0.4 m soil depth under the high N-application rates could indicate high N uptake by the plant, which could have contributed in an increase in yield under machine harvested bushes observed in the third season. The nitrate concentration in the soil solution varied between the 0 - 0.20 m and 0 - 0.60 m soil depths, however, low nitrate concentrations were recorded under high N rates. Increasing N-application rates raises concerns of leaching, especially under poor irrigation management practices or intensive rainfall events following fertilizer application. Although the high N-application can lead to high yields, they can be an economic loss to growers in terms of unnecessary input costs (Li, 2004) as N losses can be high as a result of soil erosion and leaching losses. Under the conditions of the study, it was shown that the high N rates did not lead to nitrate leaching, therefore, there was very little concern that the extra applied N was wasteful or that it would have an environmental impact. The results from this study showed that the highest income and return per dollar invested was realized under HHM and ROM at 400 kg N $ha^{-1}$ $yr^{-1}$. Improved yields are likely to lead to higher profits and improved economic viability of the tea industry.

### 7.4 Recommendations for the tea industry

Although hand plucking still represents the ideal manner in which to maximize yield and quality of tea, this study has demonstrated that machines can be used to harvest tea with a minimal impact on yield and quality. However, certain precautions need to be taken and a number of recommendations concerning mechanical harvesting of tea can be made following this study. Variation in yield over the season, with periods of high and low yields under machine harvesting, suggests that machine harvesting should be used in the main growing season and hand plucking during the lean periods, in order to harvest as much leaf as possible. The use of machines during the main growing season ensures maximum yield and with greater area covered per day it also maximizes productivity and reduces costs as fewer people will be required to harvest the same area. The use of hand plucking in lean months mainly applies to areas where labour is plentiful. In areas where labour is scarce, machine harvesting can be used throughout the season, provided all precautions are taken to avoid depleting the maintenance foliage by over harvesting. This might entail lengthening the plucking round from the recommended 14 days to 21 days rounds, but this should be done with caution as quality is expected to be compromised but yield will be high (Madamombe, 2008, Nyasulu, 2006). Ensuring the maximization of yields under mechanical harvesting will also entail handling the machines properly. This includes fitting adjustable skids/skates under the hand-held machine and/or the use of harnesses to maintain the plucking height and avoid cutting deep into the maintenance foliage, which has a thinning effect. This is also important in maintaining a healthy maintenance layer to constantly provide photoassimilates to the growing young shoots. Adjusting the skids up and down would adjust the plucking height, ensuring some height control. The skids will also prevent the HHM from resting on the plucking table, thereby avoiding deep cuts into the maintenance foliage. For ride-on machines operating on a 14 day plucking round, the cutter bar should be raised by 1 cm after every third plucking round to avoid twig and stem die back and also to maintain the maintenance layer. This is important to ensure that the mechanically harvested bushes are not source limited and continue to supply photoassimilates to the growing shoots. Accordingly to Wijeratne (1999), reduced handling of mechanically harvested leaf resulted in superior leaf quality compared to hand plucking. This can be achieved by avoiding over packing of plucking baskets, double handling the leaf through sorting of the leaf before loading into trailers and compressing of the leaf in trailers in order to load more leaf and standing or sitting in trailers loaded with leaf.

Management practices that promote growth of maintenance foliage should be prioritised, such as proper fertilization and irrigation to avoid water stress, which delays or stops bud break. This leads to the accumulation of dormant buds in the tea bush, thereby reducing yield (De Costa*, et al.*, 2007). According to De Costa*, et al.* (2007), bushes that are nitrogen deficient become photoinhibited at higher light intensities, which further lowers bush productivity. The cost implications of extra N applications were also explored as this determines profitability of the enterprise. It was observed that the greatest income and return per dollar was realized under machine harvesting at 400 kg N $ha^{-1}$ $yr^{-1}$. The study therefore, recommends 400 kg N $ha^{-1}$ $yr^{-1}$ under machine harvesting technology in areas that enjoy the same soil and climatic conditions (Chapter 2), instead of the currently recommended 265 or 300 kg N $ha^{-1}$ $yr^{-}$

[1] for hand plucking. In areas with different soil and climatic conditions it is important to base N-application on soil and foliar results and the amount of rainfall received, as this will determine the number of split applications to avoid N leaching.

Despite the perceptions that mechanical harvesting of tea reduces black tea quality, this study found no reduction in black tea quality relative to hand plucking. Contrary to expectations, a higher concentration of dimers and trimers, which are related to black tea quality, were found under mechanical harvesting which could have led to higher valuation under machine harvesting, especially under the ride-on machine in May 2013 relative to hand plucking. This study therefore recommends machine harvesting as an alternative to hand plucking.

### 7.5 Recommendations for future research

The study showed that the yield decline as a result of the continuous mechanical harvesting of tea bushes was primarily due to indiscriminate shoot harvesting, which altered the canopy architecture, thereby reducing PAR interception in the top 10 cm of the canopy. The altered canopy architecture resulted in a depleted maintenance layer which reduced photosynthetic rates of the maintenance layer (Chapter 4). Future research should target maintaining the maintenance layer in a bid to reduce the yield decline (Chapter 6). It is recommended that in future machine harvesting should attempt to simulate the selectivity of hand plucking, which plucks only mature tea leaf, while leaving the immature buds for the next round. This will increase the number of shoot generations on the tea bushes at any one time, thereby ensuring sustained yield throughout the season. This will also ensure that the maintenance layer is left intact, and reduce the source limitation in these bushes. In Zimbabwe and Malawi 80% of the crop is produced in 5 months, between December and April (Cloughley, 1983, Owuor and Odhiambo, 1994) and therefore, it is important to maximize production by the use of machines during this period of fast shoot growth. The effect of changing the shape of the plucking table from flat plucking table to a dome-shaped plucking table should also be investigated. The idea is expose all the sides to solar radiation thereby increasing the interception of solar radiation and hence bush photosynthesis.

The effect of reducing the hectarage by the third and increase the plant population should also be explored. This will be achieved by removing every third row in the field.

The effect would be to try and increase the interception of PAR by the maintenance foliage and hence increase shoot growth as more photo-assimilate supply will be enhanced.

Since mechanical harvesting removes most of the young immature shoots, which are strong sinks (Manivel and Hussain, 1982a), containing the greatest amount of N (Dang, 2005, Kamau*, et al.*, 2008), the application of fertilizers which can be quickly taken up by the tea bushes is important. Foliar fertilizers provide that quick solution, therefore studies to evaluate the effect of foliar fertilizers under continuous mechanical harvesting are recommended as these provide a quick and readily available source of nitrogen. More frequent application of the foliar fertilizers should also be investigated. Studies on the amount of N removed through harvest should be pursued, as these provide insight into how much N is removed through harvest as yield. This can be achieved by determining the loss of N after each harvesting interval, and determine a nutrient budget, taking into account the mineralization from the decomposition of the pruned material. The use of high N-application rates calls for further research on its effect on black tea quality in terms of chlorogenic acid profiles and volatile flavour compounds. The perception is that continuous mechanical harvesting, due to the non-selective harvesting of shoots causes mechanical injury to the tea bushes and leaves and would therefore affect the concentration of these volatile flavour compounds and hence black tea quality. The 'volatile flavour index' are important biochemical indicators of the quality of brewed black tea (Wright, 2005). The volatile flavour compounds and other biochemical compounds impacting black tea quality should be studied further over a three year pruning cycle, with sampling done during the main growing period and off - season. The initial results which showed increased production of dimers and trimers under mechanical harvesting should be explored further as these are known to be important in terms of health benefits (Tanaka*, et al.*, 2009, Weerawatanakorn*, et al.*, 2015).

Most tea estates are located in high rainfall areas, meaning that compaction can be an issue, especially under the ROM and therefore needs to be explored. Compaction has been found to reduce yield in sugarcane production (Braunack*, et al.*, 2006, Naseri*, et al.*, 2007) and in most mechanized agriculture (Lindstrom and Vorhees, 1994). Furthermore there is need to carry out a complete economic analysis of the different harvesting methods of tea for a complete understanding of the financial costs and benefits of hand plucking versus machine harvesting. This will aid in the determination of the financial viability of machine harvesting compared to hand plucking.

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# APPENDIX

**APPENDIX A1 Yield decline in mechanically harvested clonal tea (Camellia sinensis (L) O. Kuntze) as influenced by changes in source/sink and radiation interception dynamics in the canopy:**

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**APPENDIX B1 List of biochemical compounds identified from made tea samples and their peak/area response values under the different harvesting methods during the main growing period (February 2013)**

| Name of Compound | Rt (mins) | Mass (m/z) | Peak/area response | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | HP 265 kg N ha$^{-1}$ yr$^{-1}$ | HHM 265 kg N ha$^{-1}$ yr$^{-1}$ | HHM 300 kg N ha$^{-1}$ yr$^{-1}$ | HHM 400 kg N ha$^{-1}$ yr$^{-1}$ | ROM 265 kg N ha$^{-1}$ yr$^{-1}$ | ROM 300 kg N ha$^{-1}$ yr$^{-1}$ | ROM 400 kg N ha$^{-1}$ yr$^{-1}$ |
| Theanine | 1.08 | 173.09 | | | 186.2 | | 213.9 | 192.3 | 213.9 |
| Theasinensin C/E | 2.4 | 609.12 | 113.0 | 0.4 | | 119.3 | | | |
| 3-p-Coumaroylquinic acid | 11.32 | 337.08 | 174.8 | | 189.8 | | 217.5 | | |
| Epigallocatechin | 11.63 | 305.05 | 63.2 | 69.7 | 94.5 | | 70.6 | 55.3 | |
| Epicatechin | 17.61 | 289.06 | 18.7 | 23.9 | 23.6 | | 10.7 | 26.1 | 26.2 |
| Theasinensin A/D | 16.03 | 913.16 | 10.3 | 11.3 | | | | | 20.1 |
| 5-p-Coumaroylquinic acid | 18.36 | 337.08 | 5.2 | 5.2 | 3.9 | | 3.4 | 9.6 | 7.8 |
| Epigallocatechin gallate | 18.41 | 457.07 | 134.3 | | | | 178.1 | | 152.6 |
| Theasinensin F/G | 20.04 | 897.16 | 0.5 | 1.6 | | | | | |
| Epicatechin gallate | 26.56 | 441.07 | | | | | 227.4 | | |
| Unknown "Theaflavin" Isomer 1 | 27.35 | 563.13 | 114.4 | | | | 125.5 | | |
| Quercetin 3-O-[β-D-Glucopyranosyl-(1→3)-α-L-rhamnopyranosyl-(1→6)-β-D-glucopyranoside] | 28.52 | 771.19 | 0.1 | 0.7 | | | | | |
| Quercetin 3-O-glucoside | 28.95 | 463.08 | 2.0 | 3.4 | 1.8 | | | | |
| Camelliaside C | 30.09 | 609.14 | 95.9 | 100.8 | 88.6 | | 79.0 | | 59.5 |
| Kaempferol 3-O-glucoside | 32.38 | 447.09 | 178.4 | 212.3 | | | 168.9 | 194.3 | |
| Theaflavin | 38.02 | 563.11 | | | 6.7 | | | 22.2 | |
| Theaflavin 3-O-gallate | 38.61 | 715.12 | 98.3 | 90.8 | | | 103.3 | | |
| Theaflavin gallate | 38.98 | 715.13 | 90.9 | | 96.7 | | 85.2 | 42.8 | 90.2 |
| Theaflavin digallate | 39.06 | 867.15 | 91.8 | | | | 105.2 | | 113.1 |

**Appendix B2 List of biochemical compounds identified from made tea samples and their peak/area response values under the different harvesting methods during the off - season (May 2013)**

| Compound identified | Rt (mins) | Mass (m/z) | Peak/area response | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | HP 265 kg N $ha^{-1}$ $yr^{-1}$ | HHM 265 kg N $ha^{-1}$ $yr^{-1}$ | HHM 300 kg N $ha^{-1}$ $yr^{-1}$ | HHM 400 kg N $ha^{-1}$ $yr^{-1}$ | ROM 265 kg N $ha^{-1}$ $yr^{-1}$ | ROM 300 kg N $ha^{-1}$ $yr^{-1}$ | ROM 400 kg N $ha^{-1}$ $yr^{-1}$ |
| Quinic acid | 0.74 | 191.04 | 19.3 | 14.4 | | | | | |
| Theanine | 1.08 | 173.08 | 106.0 | 82.8 | 87.5 | 130.0 | 88.3 | 121.6 | 86.7 |
| Theasinensin C/E | 4.45 | 609.12 | 5.5 | | | | | | 6.7 |
| Theasinensin B | 9.48 | 761.14 | 44.8 | | | 53.5 | | | |
| Epigallocatechin | 11.63 | 305.05 | | | | 72.1 | | | 98.1 |
| 3-p-Coumaroylquinic acid | 11.32 | 337.08 | 123.4 | | 115.5 | | 124.2 | | |
| Theasinensin A/D | 16.03 | 913.16 | 7.2 | | | 9.4 | | | 10.6 |
| 4-p-Coumaroylquinic acid | 16.61 | 337.08 | 7.0 | 6.9 | | | 7.0 | | |
| Epicatechin | 17.61 | 289.06 | | 218.5 | 225.3 | 129.6 | 241.3 | 204.6 | 205.3 |
| 5-p-Coumaroylquinic acid | 18.36 | 337.08 | 163.4 | 151.4 | 154.0 | | | 171.6 | 156.0 |
| Epicatechin gallate | 26.56 | 441.07 | | | | 245.4 | 360.4 | | 299.2 |
| Theaflavin | 30.06 | 563.14 | 74.1 | 78.8 | | 84.8 | | | 91.3 |
| Camelliaside C | 30.09 | 609.14 | 126.2 | 142.7 | 136.7 | | 128.6 | 121.3 | 124.1 |
| Kaempferol 3-O-glucoside | 32.38 | 447.09 | 304.0 | 292.0 | | | 283.7 | 258.5 | |
| Theaflavin gallate | 38.99 | 715.13 | 85.5 | 56.9 | | 49.3 | | | 84.8 |
| Theaflavin digallate | 39.06 | 867.15 | 52.1 | 64.2 | | 76.1 | | | 73.1 |