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

Godwil Madamombe[1], Eyob Tesfamariam[1] and Nicky Taylor[1*]

[1]*Department of Plant Production and Soil Science, Faculty of Natural and Agricultural Science, University of Pretoria, Private Bag X20, Hatfield, Pretoria, 0028*

[*]Corresponding author. Tel.: +27 (12) 4203666. ***E-mail***: *nicolette.taylor@up.ac.za*

[1]Madamombe GM: *godwilmadamombe@yahoo.co.uk*

[1]Tesfamariam E: *eyob.tesfamariam@up.ac.za*

Highlights

- Mechanical harvesting removes foliage indiscriminately and decreases tea yield.
- Desirable shoot number and mass are reduced under mechanical harvesting.
- The maintenance layer is depleted in mechanically harvested bushes.
- There are a greater number of strong sinks in mechanically harvested bushes.
- Sink/source dynamics altered by mechanical harvesting.

Abstract

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. This has led to the full mechanization of shoot harvesting, however, a reduction in yield has been observed with mechanical harvesting. It was hypothesized that the decline in yield as a result of mechanical harvesting is a result of the indiscriminate harvesting of shoots which leads to a change in sink/source and radiation interception dynamics within the canopy. As a result whole plant photosynthesis is impacted; which ultimately impacts tea bush productivity. Studies conducted at

Tingamira estate, Chipinge, Zimbabwe showed significant yield differences between hand plucking and machine harvesting treatments, with higher yields under hand plucking across all seasons (43 945 kg green leaf ha^{-1}) as compared to hand-held (35 114 kg green leaf ha^{-1}) and ride-on machines (36 268 kg green leaf ha^{-1}) ($p<0.05$). This reduction in yield was associated with a decrease in both the number and mass of desirable shoots over each season. The cause of this change was largely attributed 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 depletion of the maintenance layer in mechanically harvested bushes, as indicated by reduced fractional interception of photosynthetically active radiation in the top 10 cm in these bushes and reduced photosynthetic rates in these bushes, 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.

Keywords: photosynthesis; shoot density; shoot composition; maintenance layer; photo-assimilates

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 & 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 & 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 & Hussain, 1982a). Under hand plucking the maintenance foliage is deliberately left and allowed to accumulate below the plucking table to ensure continued production of photo-assimilates for new shoot growth. 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 & 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 C3 plants (De Costa *et al.*, 2007; Mohotti *et al.*, 2000; Mohotti & Lawlor, 2002). 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 & Lawlor, 2002).

Tea yields may also be sink-limited due to the continual removal of shoots 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 (Mohotti & Lawlor, 2002; Squire, 1977; Tanton, 1979). 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. 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.

2. Materials and Methods

2.1 Study site description

The trial was conducted at Tingamira estate, Chipinge district, Manicaland province, south eastern Zimbabwe (20° 09.13' S, 32° 48.26' E, 979 masl) on the tea (*Camellia sinensis* (L) O. Kuntze) cultivar PC 108. 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). 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 (K_p) 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 temperature of 20.7 °C. The soils are orthoferralitic (sandy clay loam) derived from mofic rocks (Chenje *et al.*, 1998) with an average pH of 4.1. These soils are highly weathered, contain few weatherable minerals and are often rich in Fe and Al oxide minerals (Chenje *et al.*, 1998), making the soils acidic.

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. Plucking rounds were according to standard management practices and are based on a compromise between yield and quality for each harvesting method. The treatments were laid out according to a randomized complete block design (RCBD). Plot size was 2.4 m x 50 m (six double rows x 333 bushes), with a spacing of 1.2 m between rows and 0.75 m within rows. Row orientation was from west to east. The Ochiai, hand-held machine, (Ochiai Cutlery Manufacturing Co Ltd, Kikugawa City, Shizuoka Japan) (Fig.1A) and a ride-on self-propelled machine (Brownes Engineering, Harare, Zimbabwe) (Fig.1B) were used throughout the study period. Height adjustment on the HHM depends 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.

Fig.1: Mechanical harvesting machines, which included (A) the hand-held Ochiai, and (B) the ride-on self-propelled tea harvester

Best management practices were applied to the experimental block in terms of weeding, fertilization and irrigation. Fertilizer was maintained at 265 kg N ha^{-1} for the three year duration of the trial period. 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 45 cm from the ground. Tipping, a harvesting operation to create an even plucking table, whilst at the same time leaving some maintenance foliage, was done at 55 cm from the ground or at 10 cm above the pruning height, on the 20th 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 60 cm 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.

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.

2.4. Shoot density, shoot composition and shoot mass determination

A 100 g shoot sample was randomly collected from each plot after each harvest for the determination of shoot composition. The sample was separated into the different shoot components, viz., buds, 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, soft banjhi, hard banjhi, half cut leaf, quarter cut leaf and broken pieces of stems and leaves. A banjhi shoot is a dormant shoot and 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. 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 65 ^{o}C 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. 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 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).

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.

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} (De Costa *et al.*, 2007; 2009; Lin *et al*., 2014; Smith *et al.*, 1993; 1994), 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 marked 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.

2.8. 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 $P<0.05$.

3. Results

3.1 Yield

In the 2010/2011 season there were significant differences in total monthly GL yield between HP and machine plucking treatments (HHM and ROM) ($p<0.001$) (Fig. 2A). 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 (Fig. 2A), 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. The first yield was recorded in October with the highest GL yields (3282 kg ha^{-1}) found in the hand plucked bushes (Fig. 2B). 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 ($p<0.05$) (Fig. 2B), 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

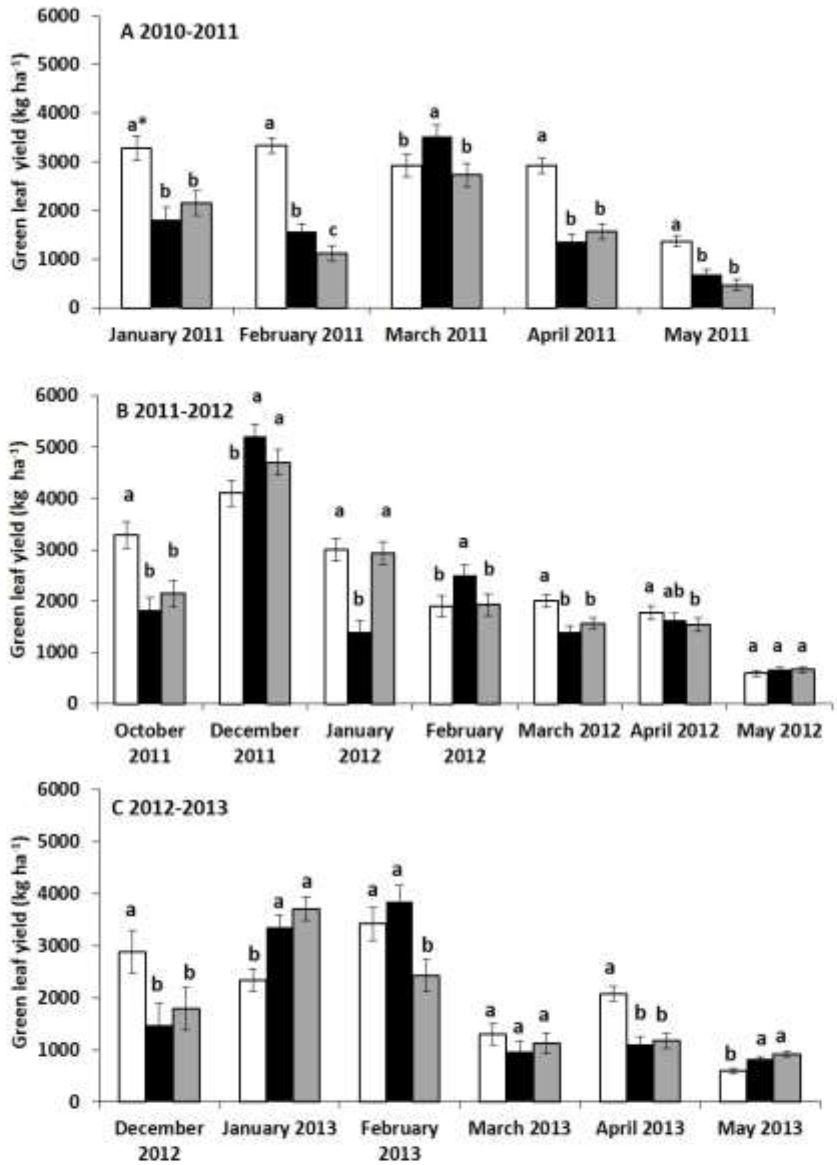

Fig. 2. Total monthly green leaf yield of PC 108 at Tingamira Estate under hand plucking ( ),hand-held machine ( ) and ride-on machine ( ) in the A) 2010/2011 season, B) 2011/2012 season and C) 2012/2013 season (kg GL ha^{-1}).

*** 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**

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 (Fig. 2C). 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 (Fig. 2C) compared to HP, which exhibited more consistent yields at this time. A decline in yield was observed in all treatments from March 2013. Hand plucking produced the lowest yield in May compared to mechanical harvesting treatments.

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 1).

Table 1. Total seasonal green leaf yield (kg GL ha^{-1}) of 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 are not significantly different from each other at p<0.05 Duncan's Multiple Range Test**

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 realised in the hand plucked treatments as compared to both mechanically harvested treatments (Table 1).

3.2 Shoot composition, density and shoot mass

3.2.1 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 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.

3.2.2 Shoot density

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 (Fig.3). Total shoot densities before or after plucking did not differ between machine harvested plots. Harvesting method also had a significant impact on the number of harvested shoots in the different shoot classes, with

Table 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

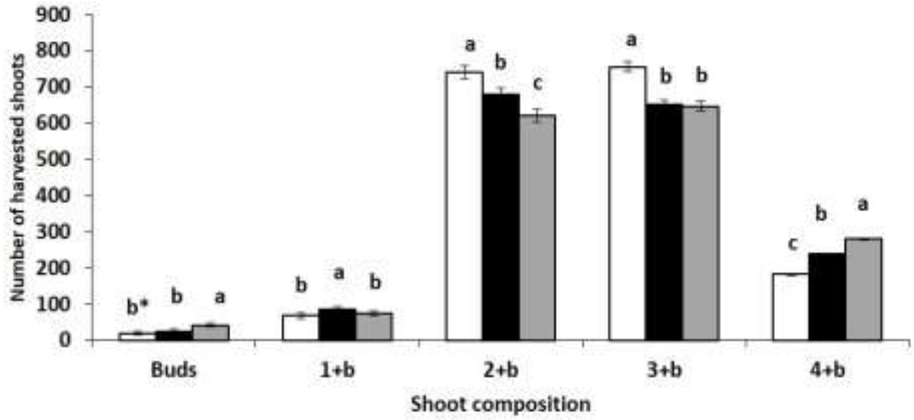

Fig.3 The effect of hand plucking ( ), hand-held machine ( ) and ride-on machine ( ) on shoot density on the PC108 tea bushes (totals over all harvests and seasons shoots m^{-2})

[*] 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

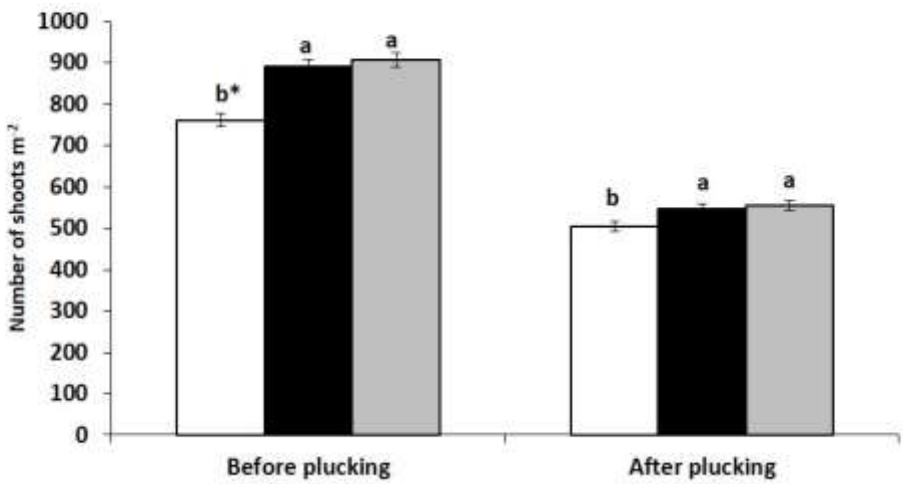

Fig.4 The effect of hand plucking ( ), hand-held machine ( ) and ride-on machine ( ) on total number of different shoot components harvested on PC 108 (totals over all harvests and seasons)

[*] 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

the ROM harvesting more buds than HHM and HP ($p<0.05$)(Fig.4). 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 (Fig.4). Significantly ($p<0.05$) more 4+b were harvested with machines than hand plucked bushes.

3.2.2 Shoot mass

There were significant difference between treatments in the average fresh and dry mass of 2+b and 3+b shoots at harvest over the three seasons (Tables 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 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

3.3 Fractional interception of photosynthetically active radiation (FI-PAR) following plucking.

As expected 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 (Fig. 5). 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.

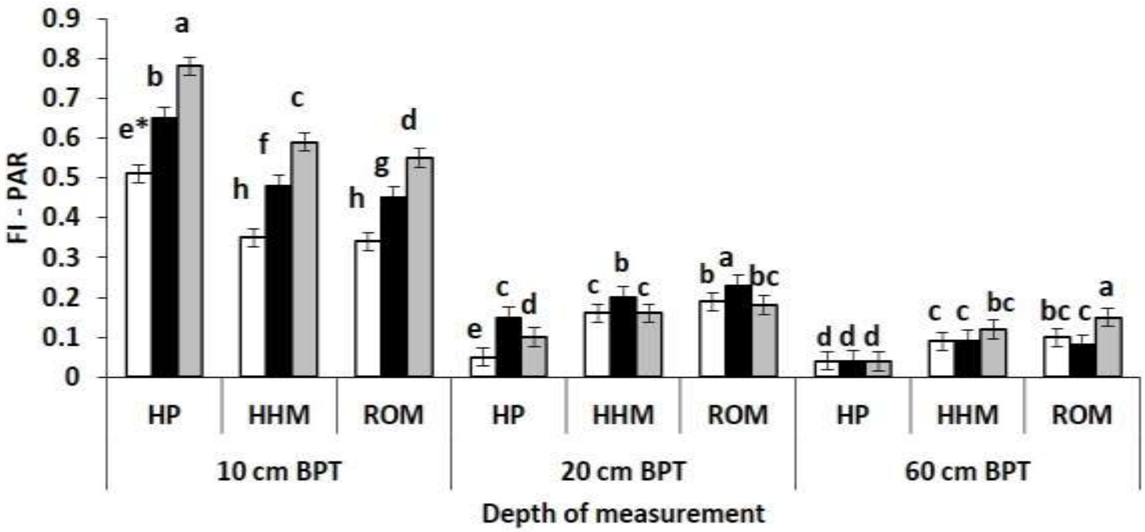

Fig.5. Mean FI-PAR dynamics within the tea bush canopy of PC 108 under different harvesting methods at 0 DAP ( ), 5 DAP ( ) and 10 DAP ( ). (DAP= days after plucking, BPT= below plucking table)

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

3.4 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) ($p<0.001$) (Fig. 6). 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 5 days after plucking and lowest at 10 days after plucking.

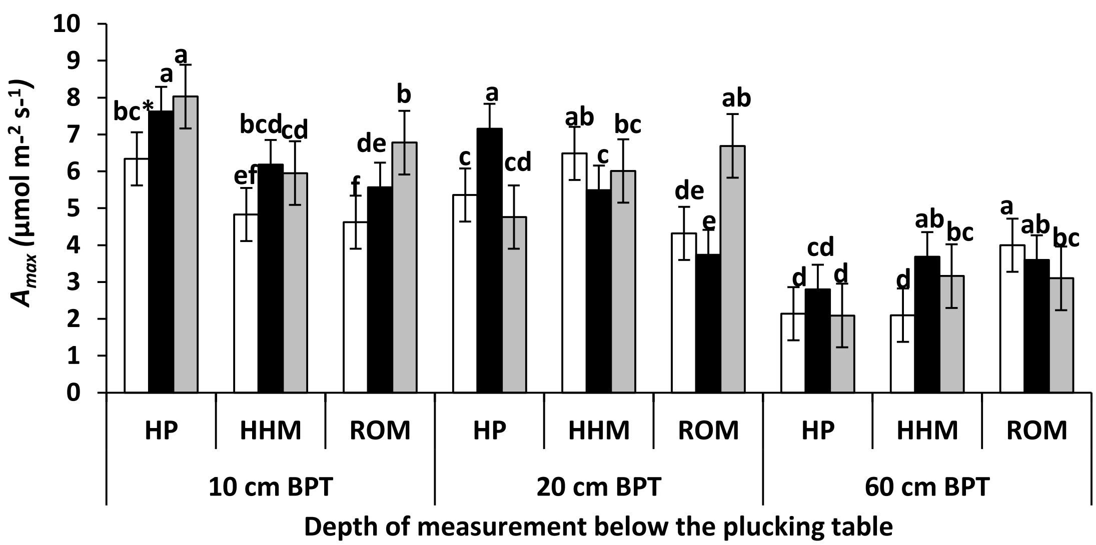

Fig.6. Photosynthetic rate (*A*), under different harvesting methods at different depths below the plucking table, 0 DAP ( ), 5 DAP ( ) and 10 DAP ( ) (DAP= days after plucking, BPT= below plucking table)

*** 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. Discussion

This study has confirmed results from previous studies (Madamombe, 2008; Mukumbarezah, 2001; Nyasulu, 2006; Wijeratne, 1999) 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 *et al.*, 2010; 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) (Madamombe, 2008; Mouli *et al.* 2006; Mukumbarezah, 2001; Nyasulu, 2006). 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 compromised 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 synchronised 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 & 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 this 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.

5. 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 results 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 maximise 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.* (2006) may aid in determining appropriate machine heights to sustain yield throughout the season, a principle that has also been demonstrated by Rahman (1988). Management practises 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.

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