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Responses of composite tea plants to drought and irrigation in the Southern Highlands of Tanzania

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ABSTRACT

The responses of composite tea plants to drought and irrigation were studied in a line-source experiment in the Southern Highlands of Tanzania. Two scion clones (S15/10 and K35) were grafted onto each of three rootstock clones (6/8, SFS150 and PC81). The scions were also grafted onto each other (i.e. S15/10 on K35 and *vice versa*), and cuttings of ungrafted clones S15/10 and K35 were prepared at the same times as the controls. In February 1996, the plants were field planted at a spacing of 1.2 x 0.8 m. Six differential irrigation treatments ranging from rainfed conditions (no irrigation) to full irrigation were imposed during the dry seasons, though from planting up to the end of August 1998, the experiment was uniformly irrigated to ensure successful crop establishment. The experiment was irrigated whenever the potential soil water deficit in the fully irrigated plots reached 40 - 50 mm. Between December 1996 and May 1997 shoots above 0.5 m in length were removed or "tipped" to produce a level plucking surface. Routine harvesting started on 16 June 1997, and continued at intervals of 13 to 17 days during the warm season (September to May) and 22 to 29 days in the cool season (June to August).

The choice of the scion influenced both the response to water stress and the yield response to drought of the composite plants. Similarly, the soil water availability appeared to modify the effects of rootstock on the yield of the scion. Although not reaching statistical significance, the use of composite plants led to an overall mean annual yield increase of 9% (range between combinations 4 to 21%) in the unirrigated plots, but less than 1% (range –6 to 6%) in the well watered plots when clone S15/10 was used as a scion. By contrast, using clone K35 as a scion, the overall mean annual yield increase whether irrigated or unirrigated was less than 3% (range –12 to 11%). In the driest plots, rootstocks 6/8 and SFS150 consistently increased the yields of scion clones S15/10 (by 21%) and K35 (by 11%) respectively. During the dry season, some composite plants survived the drought better than the ungrafted plants.

Assessing the effect of rootstocks on the composition of harvested shoots (i.e. shoots of different sizes/stages and the proportion of the total weight that were composed of coarse and broken leaf) revealed that none of the rootstocks had a significant effect on the composition of harvested shoots. Likewise, the rootstocks did not affect the bush morphology as assessed by ground cover development, shoot population density, stem diameter and number of branches.

The use of composite plants in tea production by both smallholders and commercial companies is technically feasible, but the benefits to be realised depend on the rootstock/scion combinations used. The extra cost of producing plants by grafting when large-scale tea growers opt to use composites rather than the conventional plants was estimated to be only US \$ 100 ha^{-1}. Due to low labour costs, the corresponding cost for the smallholders was US \$ 47 ha^{-1}. The payback period when composite plants were used in tea production was the same as that of the conventional plants, but this period was shorter for smallholders than the commercial companies. The payback period was in year 1 (i.e. the first season of harvesting) for the small-scale growers compared with year 2 or 3 (depending on the prices of made tea) for the commercial companies.

Assessing the probability of getting a yield increase necessary to make the use of composites worthwhile revealed that for some combinations, there were higher chances of getting such yield increase. For example, the probability of getting a yield increase of 200 kg of made tea ha^{-1} in one year was 81% when scion clone S15/10 was grafted onto rootstock 6/8. The corresponding probability was 74% when clone K35 was grafted onto rootstock SFS150.

These results and their implications for the tea industry are discussed. The way forward commercially as well as the future research to increase our knowledge for efficient use of composite plants in tea production is proposed.

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The moral support from my parents and my brothers is highly acknowledged. Lastly, my absence at home during this study has not been accepted by Jessica, my daughter. It was hard for her to understand how can a daddy be away for such long period.

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ABA	Abscisic acid	
AWC	Available water content	(mm)
B	Benefits accruing in year t	($)
BBK	Brooke Bond Kenya	
BCR	Benefit/cost ratio	
C	Cost accruing in year t	($)
d	Rate of discount	(%)
E_o	Evaporation from an open water surface	(mm day^{-1})
ET_a	Actual crop evapotranspiration	(mm day^{-1})
ET_o	Potential crop evapotraspiration	(mm day^{-1})
ET_{pan}	Evaporation from a screened evaporation pan	(mm day^{-1})
HRI	Horticulture Research International	
K_c	Crop factor	
MTC	Mufindi Tea Company	
NPV	Net present value	($)
PWP	Permanent wilting point	
SWD	Soil water deficit	
t	Number of years	
TF	Theaflavins	
TR	Thearubigins	
TRFCA	Tea Research Foundation of Central Africa	
TRFK	Tea Research Foundation of Kenya	
TRIT	Tea Research Institute of Tanzania	
UPASI	United Planter' Association of Southern India	
VPD	Atmospheric saturation vapour pressure deficit	(kPa)

CHAPTER 1

INTRODUCTION

BACKGROUND

Tea (*Camellia sinensis* L.) is believed to have been cultivated for so long that its home as a wild plant is a matter of speculation (Eden, 1965). It has been reported by Kingdon-Ward (1950), Eden (1965), Weatherstone (1992) and Phipps (1981) as indigenous throughout the forests of South-East Asia, in an area stretching from Assam in the west to China in the east and down to Vietnam in the south. Tea was initially used by the local people within its area of origin for medicinal purposes, but then as a refreshing beverage (Squire and Callander, 1981; Weatherstone, 1992).

Tea genotypes are known to be grouped into two major types based on their origin: China-type plants with small upright leaves, which in their natural state, can grow into a tree 1 – 3 m high; and Assam-type plants with larger horizontal leaves can grow 9 - 15 m tall (Weatherstone, 1992; Wight, 1962, cited by Stephens, 1991). As their names suggest, the China-type is believed to have originated from China and the Assam-type from Assam, India.

Although tea originated in South-East Asia, it is now grown in many other parts of the world, from latitude 42° N to 27° S and between sea level and 2,600 m altitude (Matthews and Stephens, 1998). Despite tea being grown in other parts of the world, however, India and China remain the main world's largest tea producing countries (TeaTalk, 1999; Teatrend, 2001).

As one would expect, the variation in latitude and altitude means that the tea growing areas of the world experience different climates and day-to-day weather conditions (Carr, 1972; Carr and Stephens, 1992; Laycock, 1964; Squire, 1979; Stephens *et al.*, 1992; Tanton, 1982). Temperature, solar radiation, rainfall and vapour pressure deficit are the major weather variables which affect the growth and yield of tea.

Progress of the Tanzanian tea industry over years

In Tanzania, tea was introduced for the first time by the German settlers in 1904 (Carr *et al.*, 1988). It was planted in Usambaras (North) and in Tukuyu in the South. These areas together with Kagera (North-West), Njombe and Mufindi in the Southern Highlands are the main tea growing areas in Tanzania (Figure 1).

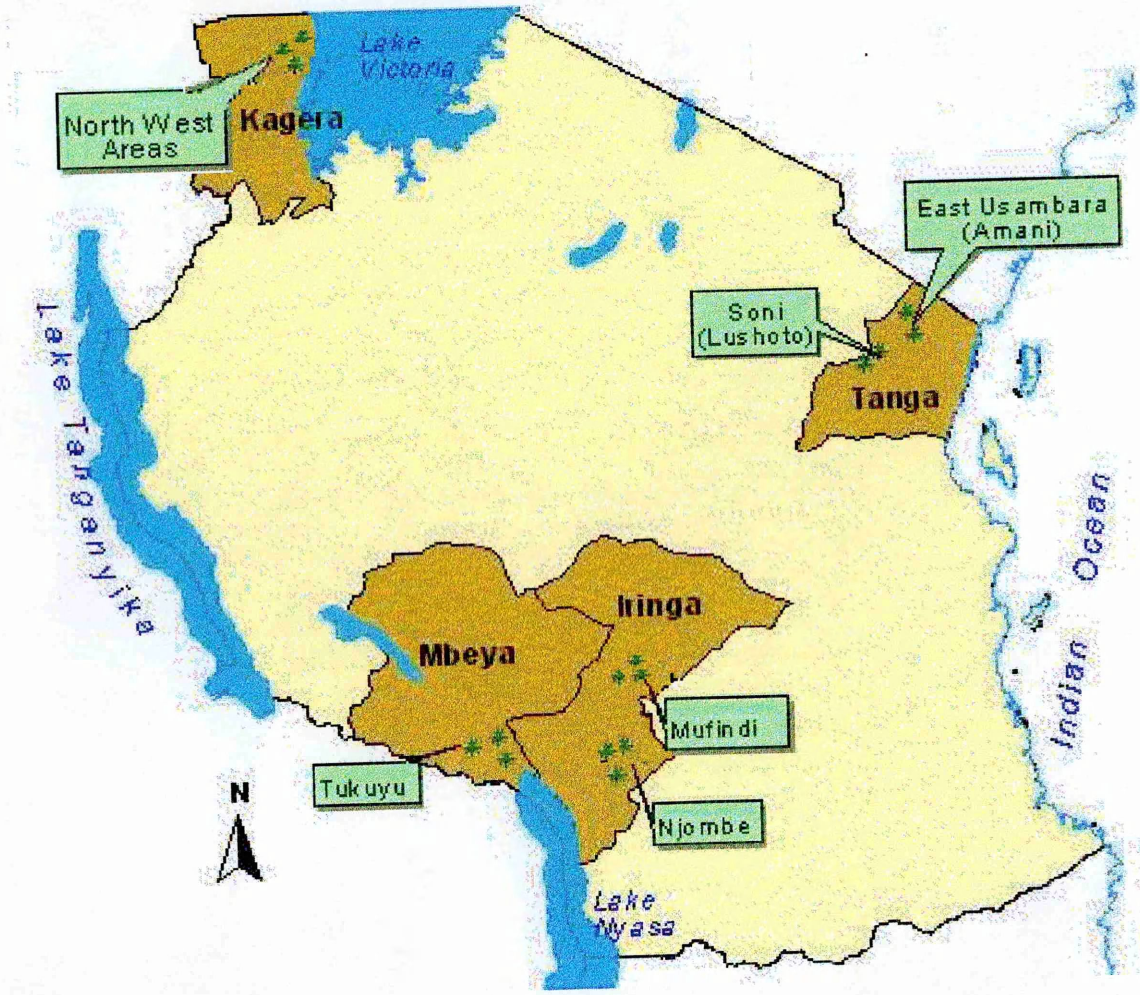


Figure 1: The main tea growing areas of Tanzania

National tea production

Although tea was introduced in 1904, commercial production started in 1926 (Carr *et al.*, 1988). Currently, the total area under tea in Tanzania is estimated to be 23,300 ha (about half of which belongs to smallholders) producing up to 25,000 tonnes of made tea per year. Of the total area under tea, only about 4,470 ha (about 19%) is under irrigation. Tea production in the remaining area depends entirely on rainfall.

Of the national tea production, about 65 – 70% is produced in the southern tea growing areas with Mufindi district being the main tea producing district in the country, with about 35 - 40% of the national crop. Figure 2 summarises the national tea production for the period between 1955 and 1999. The production increased steadily between 1955 and 1979. This was primarily due to the increase in area under tea, but also there were technological and management changes during this period (see below).

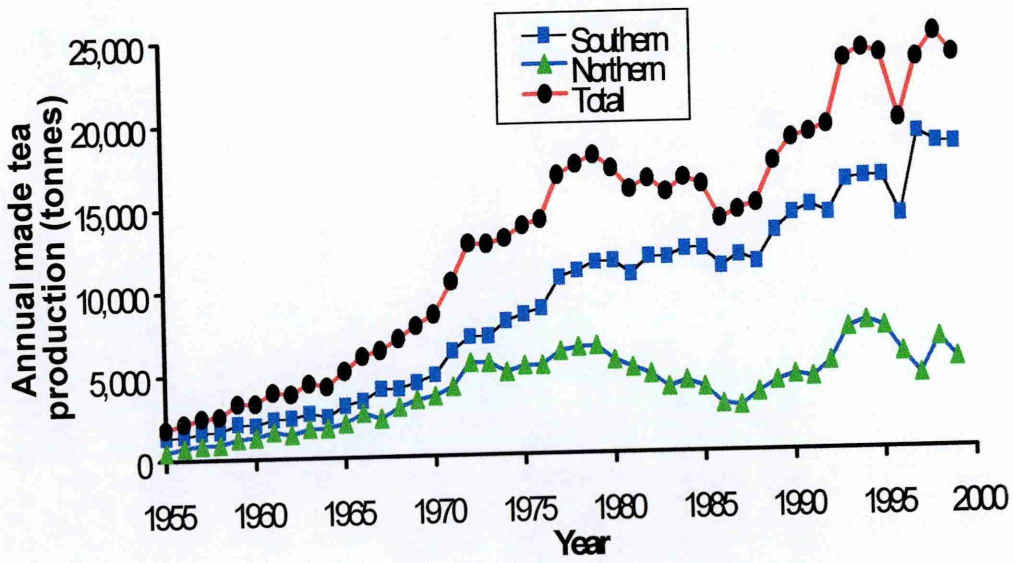


Figure 2: Tanzanian national tea production for the period 1955 to 1999.

During the period between 1980 and 1988, the production dropped and remained lower than that of 1979. This drop was mainly caused by political environments where private investments were not encouraged. The decline in tea prices in the world market which resulted in tea growers abandoning their fields (e.g. some estates in the Usambara Mountains) as production became uneconomic (Carr, 1999) also contributed into the decrease in the national tea production.

Nevertheless, the Tanzanian tea industry has achieved remarkable progress. Annual yields of processed tea have been increased from 500 – 1,000 kg ha^{-1} in 1960s to 3,000 - 4,000 kg ha^{-1} in 1990s on many estates in East Africa (Stephens *et al.*, 1994). In recent years average annual yields in excess of 4,000 kg ha^{-1} have been recorded from the best estates in the Southern Highlands of Tanzania. By comparison not much has been achieved to improve the yields from smallholders over the same period. In fact the reverse occurred, yields from smallholders decreased from about 500 - 600 kg ha^{-1} in the mid-1980s to the current production of 200 kg ha^{-1} (Carr, 1999). The poor performance of this sector however, was a special case mainly caused by mismanagement by the Tanzania Tea Authority, the parastatal organisation responsible for smallholders.

Technological and management changes

The yield increases per unit area described above were achieved through a number of both technological and management changes in the tea industry. Introduction of irrigation in early 1970s as well as a steady increase in fertilizer application rates are among the major changes took place over the years. Similarly, changes in the plucking standards (from two to three leaves and a bud), replacing manual weeding with hand hoes by herbicides and the use of improved planting materials are other changes that increased the production (Carr, 1999). As mentioned earlier, these changes were more pronounced in the commercial companies than in the smallholders sector.

The change from using seedling tea, which is described to be of low yield potential and/or low yield responses to inputs (e.g. fertilizers and irrigation) as well as poor quality (Limwado, 1995) to clonal tea in 1960s had a major impact in the tea industries in many tea growing regions of the world. Since then, as a result of plant improvement programmes, a number of improved clonal materials with desirable attributes such as yield, quality and drought tolerance have been released. On many occasions however, these attributes are found separately in individual clones. That is, a higher yielding clone may not be of good quality, or a drought tolerant clone can be of low yielding and/or poor quality. Exploiting the positive attributes from the individual clones to increasing production both in terms of quantity and quality therefore has been difficult.

One method of combining the best attributes of individual cultivars is to use grafting to create composite plants. The early work on composite tea plants showed the potential of these plants to improve attributes such as yield and/or quality and drought tolerance of the clones used as scions. For example in Malawi (TRFCA, 1995), for the period of 15 years, grafting scion clone PC80 onto rootstocks PC87 and MFS87 improved its annual yields by 54 – 206%. In Kenya, the potential of some rootstocks to improve yields has been realised at Brooke Bond Kenya Limited (Corley, 1991; Smith and Bayliss, 1994).

Likewise, in India and Sri Lanka, the yields from composite tea plants were reported to be higher than those of their respective ungrafted scion clones (Pallemulla *et al*., 1992; Satyanarayana *et al*., 1991).

The previous work has also demonstrated that some composite plants can survive drought better than their respective scion clones when planted on their own roots. For example during the 1986/87 drought in Malawi, only 74 and 79% of clones PC80 and SFS204 respectively on their own roots (ungrafted) survived the drought compared with 100 and 99% when grafted onto rootstock PC87 (Nyirenda and Mphangwe, 2000). Similar results were reported in Kenya (Bore, 1997; Corley, 1991), India (Satyanarayana *et al*., 1991; UPASI, 1983) and Sri Lanka (Pallemulla *et al*., 1992).

Over the years, work on composite tea plants by different researchers has generated useful information on the role of composite tea plants in tea production. Apart from the benefits described above, the previous work has also shown that there were graft incompatibilities between some rootstock/scion combinations (Barua and Sakia, 1973). The benefits to be realised from composite tea plants therefore depend entirely on the selection of the rootstock/scion combinations.

Although a number of studies have been conducted with composite tea plants in several countries, rarely have the results been reported systematically in a way in which it is easy to quantify the benefits in diverse situations. Likewise, the previous work has not clearly addressed some key areas, which would have broadened our understanding on the potential role of composite plants in tea production. Firstly, the responses of composite tea plants to irrigation or drought have not been quantified. Although drought tolerance is one of the benefits reported in the previous work, little has been done to assess this attribute in a wide range of water regimes. This is very important because the information is useful to both large and medium-scale commercial producers, who can afford to irrigate (fully or partially) their fields, and to the smallholders who depend entirely on rainfall.

Secondly, no clearly defined selection criteria to enable tea producers and scientists to select and match rootstock/scion combinations with confidence. Nyirenda (1987) supported this view, when he concluded that until the right selection criteria for both rootstocks and scions have been fully established, it will continue to be a game of chance. In the previous studies combinations were selected based on good agronomic characteristics of the individual clones. For example, at Brooke Bond Kenya Limited, rootstocks were selected during drought years by selecting clones that had survived the drought period (Corley, 1999). Likewise, scions were selected on the basis of quality as well as ease of harvest. A similar approach has been used for selecting rootstocks and scions in India (Satyanarayana *et al*., 1991). Matching scions to the appropriate rootstocks, however, was guesswork. No short term measure for matching rootstocks and scions is available. Testing a large number of combinations and then rejecting those that are not compatible is the only way, which is time consuming and expensive.

Thirdly, the quality of the leaf produced by composite plants as compared to the quality of the leaf from their respective scion clones grown on their own roots has also not been properly studied. These areas need to be addressed for efficient use of composite tea plants in tea production.

OBJECTIVES

The aim of this study is therefore to develop further understanding of the role of composite plants in tea production with the following specific objectives:

1. To evaluate the water use and the responses to water stress of selected rootstock/scion combinations;
2. To evaluate the yield responses to drought and irrigation of selected rootstock/scion combinations;
3. To assess the effect of rootstocks on the composition of harvested shoots;
4. To seek to specify criteria for matching rootstocks and scions to create composite plants that are adapted to specific environments; and
5. To specify the circumstances under which the use of composite tea plants is likely to be financially viable.

This thesis presents the results of a study on the responses of composite tea plants to drought/irrigation. The thesis comprises nine chapters as summarised below:

Chapter 1: deals with the background information and the introduction of the study subject. The aims and the objectives of the study are presented in this chapter.

Chapter 2: presents a review on the role of composite tea plants in tea production. Problems and successes are also discussed.

Chapter 3: summarises the general methodology of the study, which includes soils data, and the climate and weather conditions of the site. Procedures for producing composite plants and the experimental design as well as the statistical analysis are covered in this chapter.

Chapter 4: describes the water use and the responses to water stress of different rootstock/scion combinations under different water regimes.

Chapter 5: reports the yields and yield responses to drought and irrigation. The yield trends over years are also covered.

Chapter 6: examines the effect of rootstocks on the composition of the harvested shoots.

Chapter 7: covers the effect of rootstocks on the bush morphology as assessed by the crop cover development, shoot population density, stem diameter and the number of branches of the scions.

Chapter 8: deals with the economic analysis in attempt to quantify the benefits of using composite plants in tea production.

Chapter 9: summarises the main conclusions and recommendations of the study. The way forward commercially and future research are proposed.

CHAPTER 2

THE ROLE OF COMPOSITE PLANTS IN TEA PRODUCTION: A REVIEW

INTRODUCTION

In the horticultural industry, the practice of grafting has been used for many years with the primary objective of improving attributes such as yield, quality, growth habit, precocity and disease resistance of the scions, as well as a means of rapid multiplication of improved cultivars (Hartmann *et al*., 1990; Tubbs, 1973a; Webster, 1995b). In an attempt to explain the influence of the rootstocks on the scions, recent work at the Horticulture Research International (HRI), United Kingdom (Webster, 1995a), has shown that rootstocks might directly influence scion tree vigour in one or more ways by delaying scion vegetative budburst and the onset of shoot extension, influencing rates of shoot extension, affecting branching habit and altering the partition of the tree's assimilates and minerals between fruits and shoot growth. Apical dominance, via axillary bud dormancy and growth, possibly associated with hormone synthesis or distribution within the scion, is likely to be responsible for at least some of these phenomena.

Although the mechanisms by which rootstocks influence the scions is not clearly known, grafting has been successfully used to classify two major groups of rootstocks, dwarfing and vigorous. Apple rootstocks such as M.8 and MM.104 are examples of dwarfing and vigorous rootstocks respectively (Tubbs, 1973b). Depending on the interest, to increase or decrease vegetative growth, these rootstocks have been used effectively to increase the profitability of the horticulture industry.

In spite of these achievements, in the absence of clear selection criteria, the problems associated with graft incompatibility between some rootstock/scion combinations, appear to limit the potential of composite plants in the horticulture industry. For example, Brennan *et al*. (1998) found that in *Leucaena* composite plants, the rootstock effects depends on the specific scion and rootstock combinations. In fruit trees, Tubbs

(1973a) reported that at any time the roots or shoots or their interaction may provide the limiting factor to the growth of the whole tree. All these findings suggest that the mutual interactions and therefore the benefits of composite plants depend entirely on the rootstock/scion combinations used. The maximum benefits of using composite plants then can only be achieved if the scions are matched to the appropriate rootstocks to create plants with desirable attributes. Despite the many studies being conducted on horticultural crops (e.g. Webster, 1995; Zelleke and Kliewer, 1979; Tubbs, 1973; Adriance and Brison, 1979; HRI, 1997) the mechanisms to explain the observed behaviour of the composite plants is still not known. As a result, scientists have not yet been able to define clearly the criteria for selecting and matching rootstocks/scion combinations. The traditional ways of selection, by evaluating many combinations and rejecting those that are not compatible, which are both expensive and time consuming, are therefore still used. A proper understanding of rootstock/scion relationships and of the mechanisms underlying them are areas which deserve more attention to enhance the potential of composite plants in the horticulture industry.

PLANT IMPROVEMENT IN TEA

Initially tea was propagated using seeds, and plants derived from heterogeneous seeds still represent a substantial proportion of the planted area in many countries. For example, in Malawi, South Africa and Zimbabwe tea grown from seed covers about 64, 72 and 60% respectively of the total (Martin, 1998), whilst in Tanzania it is about half (Kimambo, 2000). Similarly, in Kenya even the most progressive companies such as Brooke Bond Kenya Limited and African Highland Produce Limited around 65 – 75% of the total area is still derived from seeds (Huq, 1996). Apart from inherent low yielding levels of the seedling tea, the genetic differences of each individual bush within the population creates a lot of field management difficulties (e.g. planning harvesting intervals). The quality of leaf harvested may therefore suffer and the average price per kilogram of made tea from seedling invoices can be consistently lower than from clonal tea (Mputeni, 1998).

To ensure the long-term productivity and competitive edge of the tea industry, it is essential to replace tea derived from seeds with improved genotypes (Limwado, 1995). This view has been supported in some commercial estates, such as Esperanza and Lujeri in Malawi (Huq, 1996) and Mufindi Tea Company (MTC) in Southern Tanzania (Ghaui, 1998), where old seedling tea is being replaced by improved cultivars. This demonstrates the awareness of tea growers about the use of improved tea cultivars. However, despite of this awareness, the problems associated with the economics (long pay back period), the difficulty of the whole exercise of uprooting and replanting, and in some cases the apparent poor performance of replanted tea (Bore, 1999), appear to limit the programmes.

Following the research work done in India and Sri Lanka in the 1930s (Banerjee, 1992), vegetative propagation techniques were introduced in the tea industry, which led to the first step in the tea plant improvement cycle. This was the introduction of clonal tea. Since then, almost all the newly established estates and smallholders' fields are planted with clonal tea. In recent years composite plants have also been used. Figure 3 summarises the tea plant improvement cycle that many tea growing areas have gone through. Profitability (both quantity and quality) has been the main driving force behind this cycle.

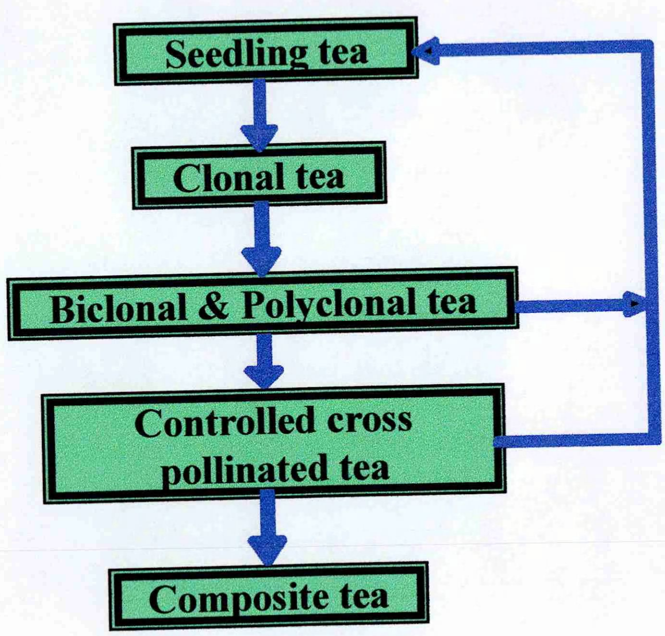


Figure 3: Tea plant improvement cycle

To facilitate the availability of improved tea genotypes, plant improvement programmes have been established in many tea growing areas. For example, techniques for improved vegetative propagation and grafting of seed bearer trees were introduced in Malawi

(Ellis and Nyirenda, 1995). As a result of these programmes, large numbers of improved tea cultivars have been released. Some are higher yielding but their quality potential is poor, some are good quality but are low or moderate yielding and others are low yielding but can withstand adverse weather conditions (Pallemulla *et al*., 1992). Grafting has been used to create composite plants in attempts to combine these attributes and other agronomic traits into one tea bush (Pallemulla *et al*., 1992; Satyanarayana *et al*., 1991). In Malawi (Kayange, 1990; TRFCA, 1995), Kenya (Corley, 1991; 1992) and India (UPASI, 1983; 1984; 1978), grafting tea in the nursery and evaluation of the field performance of the resultant composite plants has indicated the potential for some rootstocks to boost growth and yield and to improve drought tolerance of the scions.

COMPOSITE TEA PLANTS

Grafted tea plants have been used for many years. The primary objective of tea grafting was to get clonal seeds or clonal cuttings quickly. When a tea tree which has reached seed-bearing age, is grafted with a clonal scion, the scion can give a good crop of cuttings in less than two years and seeds in less than three years after grafting (Templer, 1971). To facilitate the multiplication of improved cultivars, grafted seed bearers were established in many tea growing areas. For example, during the Tea Research Institute of East Africa, a grafted seed barie was established at Rwebitaba Tea Research Station, Uganda (Templer, 1971). Similarly, in Central Africa (Nyirenda, 1995) and South India (Satyanarayana *et al*., 1991) grafted seed baries were initiated.

In recent years, the objectives of tea grafting have been extended further to include improving attributes such as yield, drought tolerance and disease resistance of the clones used as scions. This has been possible after the invention of the technique of grafting fresh, unrooted clonal cuttings in the nursery, which enables to produce grafted plants for large-scale planting (Satyanarayana *et al*., 1991). The benefits of using composite tea plants have been clearly demonstrated by the experimental work (see below) as well as the commercial experiences, such as Brooke Bond Kenya Limited (Corley, 1999) where composite tea plants cover over 300 ha, and some estates in Malawi, Zimbabwe and South Africa where over 100 ha are under composite tea plants

(Martin, 1998). The area under composite plants in these countries, however, represents very small proportion of the total area planted with tea.

Previous experimental work on composite tea plants

Selecting and matching rootstocks and scions is important in order to create compatible composite plants with the expected attributes. In tea, this has been clearly demonstrated by work in Malawi (Nyirenda, 1995; TRFCA, 1995), Sri Lanka (Pallemulla *et al*., 1992), Kenya (Corley, 1991; 1992 ; TRFK, 1985; 1989; 1996) and India (UPASI, 1978; 1982; 1985; 1992), where among the combinations evaluated only some of them improve the expected attributes. Satyanarayana *et al.,* (1991) supported this view, and found that drought tolerance, yield and production of biomass of clone scions varied with rootstock used, implying that for maximum benefits, scions have to be matched to the appropriate rootstocks. The following are the important tea clone characteristics stated in the literature for selecting rootstocks and scions:

Rootstocks

Drought tolerance: tea bushes surviving after severe drought have been selected as rootstocks. The selection is based on visual assessment in the field in the dry season. For example, in India rootstock clones UPASI-1, UPASI-2, UPASI-6 and UPASI-9 were chosen in the field during the dry season (Satyanarayana *et al*., 1991). Similarly in Malawi rootstock clones MFS87 (Ellis and Nyirenda, 1995), JSR7, RS113, RS193 and RS245 (TRFCA, 1995) were chosen for their drought tolerance.

Vigorous growth: Nyirenda (1995) stated that vigour and yield of a bush depend largely on the capacity of its roots to grow vigorously and explore a large volume of soil, absorbing sufficient quantities of nutrients to allow for the free growth of the above ground parts. Tea clones with this capacity make ideal rootstocks. For examples, in Malawi (Ellis and Nyirenda, 1995; Nyirenda and Kayange, 1984) clones PC87, MFS87, MFS97 and PC81 were selected as rootstocks on the basis of their vigour. Similarly, in Kenya (TRFK, 1997) clones 6/10, 8/112 and 39/10 were selected as rootstocks on the same basis.

Recovery from prune: rootstock clones JSR7, RS113, RS193 and RS245 are selected as rootstocks in Malawi (TRFCA, 1995) due to their capacity to recover quickly from prune.

Capacity to grow under minimum management and agronomic inputs: tea clones that can grow under low management (e.g. not regularly weeding) and agronomic inputs (such as fertilizer and pesticides) have been selected as rootstocks in Malawi (Nyirenda, 1993; TRFCA, 1995). This is most important if the selection of the rootstocks is for smallholders. Experience has shown that most of the tea in smallholders' fields receives minimum management and low inputs. These fields are ideal for identifying bushes that can grow under such stressful field conditions.

Deep root systems and larger dry weight ratio of storage to feeder roots: Nyirenda (1990) based on his work on determination of root growth characteristics and rootstock vigour in tea found that clones with deep root systems and high ratio of storage to feeder roots dry weight proved to be good rootstocks. Rootstock clones PC87 and MSF87, which are regarded as standard rootstocks in Malawi are examples of clones with these attributes.

Scions

Yield and drought tolerance: in India (UPASI, 1989) high yielding but drought susceptible clones such as UPASI-3, UPASI-8 and UPASI-17 are selected as scions.

Quality: in Kenya, clones with good quality but susceptible to drought (e.g. 6/8), low yielding but good quality (e.g. clones 11/26 and 57/15) and good quality but slow grower (e.g. clone 31/11) are selected as scions (TRFK, 1984; 1985).

Ease of plucking: tea is mainly plucked by hand in most tea growing areas of Africa. Ease of plucking or "pluckability" is affected by: the way the shoots grow clear of the older leaves, the length of the internodes, and the softness and evenness of shoot distribution over the plucking table (Ellis and Nyirenda, 1995). Tea clones with these characteristics are selected as scions.

Nursery performance of grafted plants

In tea, the methods of grafting such as cleft grafting, chip budding, stub grafting and splice grafting are used (Nyirenda, 1990; Kayange *et al.*, 1981; Kayange, 1988; Kayange, 1990; Satyanarayana *et al*., 1991; UPASI, 1978; 1979; 1980; TRFK, 1984; 1988; Pallemulla *et al*., 1992; Barua, 1968). Comparison of nursery success rates (which is normally defined as the number of plants that died divided by the total number of plants prepared multiplied by 100) of plants grafted by different methods has shown some differences. In Malawi, Kayange *et al*. (1981) reported that the success rate of the plants in the nursery grafted by chip budding (86%) was higher than stub-grafting (60%). The work also revealed that chip budding forms stronger union than stub grafting. In India (UPASI, 1980), cleft and splice grafting were compared, with the ungrafted plants used as controls. The results have shown that the highest mean success rate was obtained from splice grafting (58%), followed by the ungrafted scion (55%) and cleft grafting (43%). But generally, these success rates are all seem to be fairly low. In subsequent reports the author reported that there were no differences in the success rates of the two methods.

Although other methods of grafting are used, chip budding and cleft grafting seem to be the most used methods of grafting in many tea growing areas. However, it appears little have been done in comparing the effectiveness of the two methods. As a result, no clear guidelines in aspects such as labour requirement are provided to tea growers to enable them to select the appropriate method of grafting. A systematic evaluation to include the nursery performance, cost of producing plants and maybe field performance of the plants produced by the two methods would be useful.

A number of experiments to compare the success rate of grafted plants and their respective ungrafted scions in the nursery have been conducted in India (UPASI, 1978; 1979). The success rates reported were in the range 4 - 80%. Work in Malawi (Nyirenda, 1995) has shown that in some cases the success rate of composite tea plants has been much better than the ungrafted scions. For example, while the success rate of the ungrafted PC108 was 63%, the success rate when grafted onto rootstock PC87 was 83%. Nyirenda reported a success rate of 98 and 70% from scion clone PC80 grafted onto rootstocks PC87 and MFS87 respectively. These success rates were obtained from nurseries under commercial estates conditions. A recent survey carried out in Malawi (Nyirenda and Mphangwe, 2000) confirmed that some estates are getting success rate of up to 95%.

There is greater variation in the success rates reported in the literature, not only between, but also within tea growing areas. It is difficult to compare results from different tea growing areas due to the fact that the methods of grafting used and clone combinations tested may be different. Similarly weather conditions and nursery management practices may not be the same. Nevertheless, the previous work demonstrates that high success rates of grafted tea plants in the nursery can be achieved if the appropriate method of grafting is applied to the correct rootstock/scion combinations under proper nursery management.

Yield assessment

Central Africa: Nyirenda (1987) reported the results of a study in which two scion clones (PC80 and SFS150) of contrasting rooting and yield potentials were grafted onto five rootstocks (MFS61, MFS87, MFS97, PC81 and PC87). The inherently shallow rooting and low yielding clone PC80 responded positively to all the rootstocks, whereas the deep rooting, high yielding clone SFS150 rarely showed a positive response to being grafted as compared to when planted ungrafted. A number of trials were carried out in Malawi between 1973 and 1982 to evaluate the performance of some clones as rootstocks. The results led to the release of two invigorating rootstock clones PC87 and MFS87. These clones are regarded as standard rootstocks in Malawi due to their capacity to improve the yields and drought tolerance of many clones used as scions (Nyirenda, 1990; Nyirenda and Kayange, 1984; TRFCA, 1995). Similarly, clone PC80 is considered to be standard "indicator" scion. Assessing the annual yield performance of these combinations in a long-term has shown that scion clone PC80 when grafted onto rootstock clones PC87 and MFS87 out-yielded the ungrafted PC80 for fifteen years with no indication of the benefits diminishing with time (Figure 4 a) (TRFCA, 1995). On the other hand, there were no yield benefits when scion clone SFS150 was grafted onto the same rootstocks. The benefits tended to decline, indeed to become negative as the bushes matured (Figure 4 b).

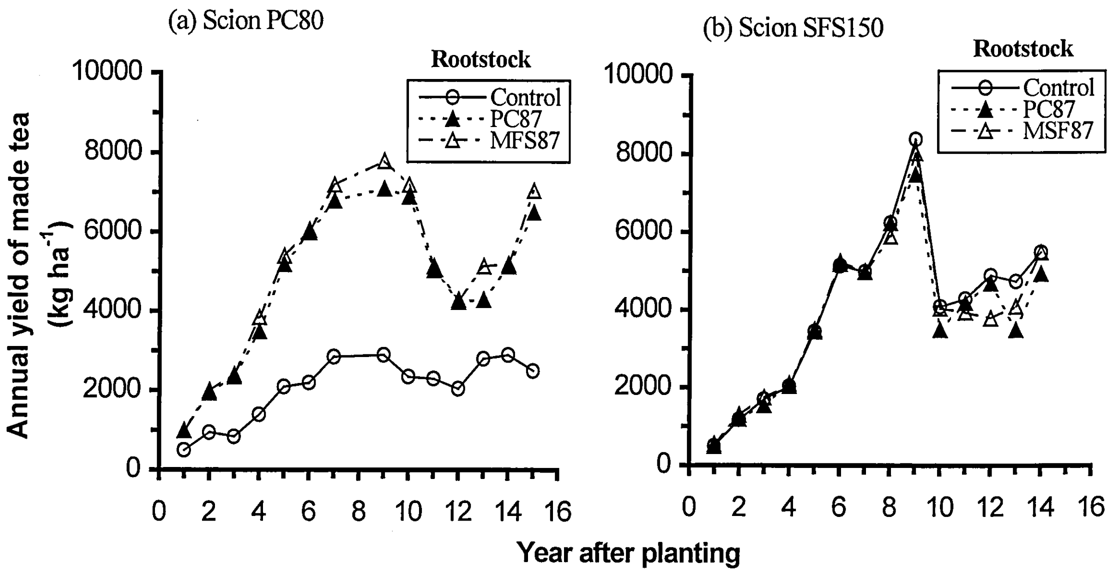


Figure 4: Annual yields from (a) scion PC80 and (b) scion SFS150 grafted onto rootstocks PC87 and MFS87 with year after planting (in December 1979). Control refers to the ungrafted scions. The experiment was conducted at Mimosa, Mulanje, Malawi. Redrawn from TRFCA (1995).

East Africa: at the Tea Research Foundation of Kenya (TRFK) a number of trials were conducted to evaluate clones as scions and rootstocks. All rootstock/scion combinations tested did not improve the expected attributes (Bore *et al.*, 1995; TRFK, 1996). Figure 5 presents the yield trend of some of the combinations from a trial by TRFK, where scion clones 6/8, 11/26, 31/11 and 57/15 were grafted onto rootstocks 8/112, 6/10 and 39/10.

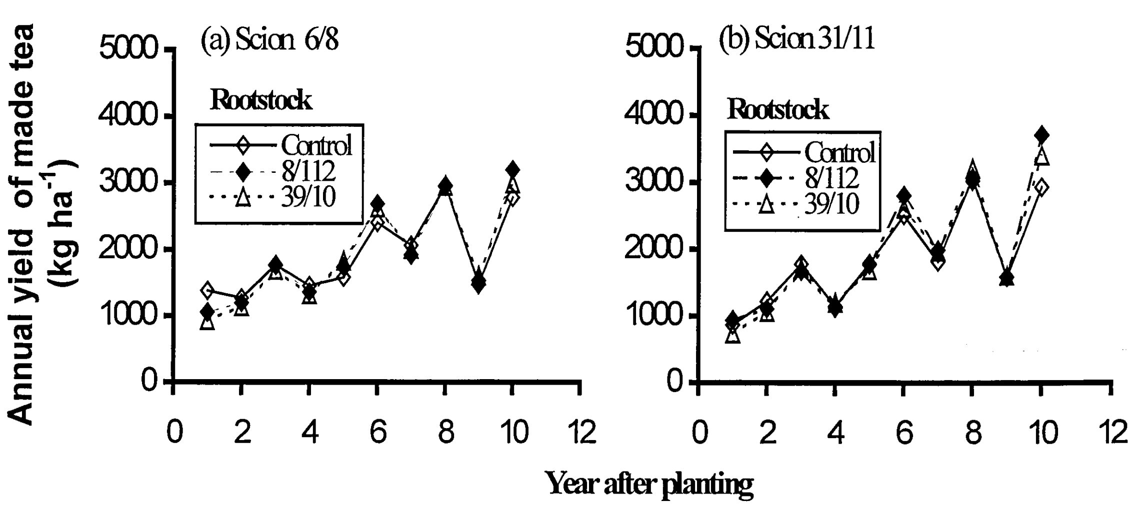


Figure 5: Annual yields of a) scion 6/8 and b) scion 31/11 grafted onto rootstock clones 8/112 and 39/10 with year after planting. Control refers to the ungrafted scions. The experiment was conducted at Timbilil, Kericho. Redrawn from TRFK (1997).

Over the period of ten years, the yields from the grafted plants were consistently the same as those from their respective scions when planted ungrafted.

Brooke Bond Kenya Limited (BBK) has conducted a number of composite plants trials at Kericho (Corley, 1991; 1992). Contrary to the results of the experiments at TRFK in which there were no yield benefits from grafting, some rootstocks improved the yield and drought tolerance of the clones used as scions. These different findings between TRFK and BBK were mainly due to the differences in the rootstock/scion combinations evaluated. In one of the trials at BBK, six clones (S15/10, 31/8, TN14/3, K35 and 152) were tested as both rootstocks and scions. Yield data collected over the first 15 months showed that rootstock TN14/3 consistent improved the yield of the clones used as scions (Corley, 1991). Similarly, the mean annual yields across scion treatments (means of five seasons) (Table 1) showed that rootstock TN14/3 continued to improve the yields of the scions as compared to the other rootstocks tested. The work revealed that there were clear differences in severity of drought symptoms attributed to both rootstocks and scions.

Table 1: Effects of rootstock clone on the mean annual yield (for five seasons, 1990 to 1995) of made tea from six scions at Ngoina estate, Brooke Bond Kenya Limited, Kericho, Kenya. The plants were planted in the field in 1989. Data from (Corley, 1999).

	Yield of made tea (kg ha^{-1})						
	Scion						
Rootstock	S15/10	152	31/8	K7	K35	TN14/3	**Mean**
S15/10	4,450*	3,740	4,670	4,220	4,490	3,680	**4,210**
152	4,470	3,950*	4,240	3,940	4,150	3,320	**4,010**
31/8	4,470	3,860	4,200*	3,750	4,410	3,300	**4,030**
K7	4,290	3,790	4,400	3,770*	4,300	4,310	**3,990**
K35	4,390	3,890	4,300	3,860	4,290*	3,400	**4,020**
TN14/3	4,920	4,210	4,710	4,230	4,440	3,860*	**4,400**
Mean	**4,530**	**3,900**	**4,420**	**3,960**	**4,350**	**3,490**	**4,110**

s.e.d. between rootstock treatments = 89 kg ha^{-1} (df = 5); scion treatments =137 kg ha^{-1} (df = 5); CV = 3.5%.

* *Yield of the ungrafted scions*

South India: work in India (UPASI, 1983) showed that when scion clones UPASI-3, UPASI-8 and UPASI-17 were grafted onto rootstocks ATK-1, UPASI-2, and UPASI-24, they out-yielded their corresponding ungrafted scions at three to four years after field planting. Similarly, the work revealed that composite plants withstood drought better than the ungrafted scions. Figure 6 summarises the yield performance of some of the combinations from this experiment. The evaluation of these combinations came to the end at the second pruning cycle, when the annual yields increase of the grafted plants as compared to their respective ungrafted scions was found to range between 4 and 21% (UPASI, 1989).

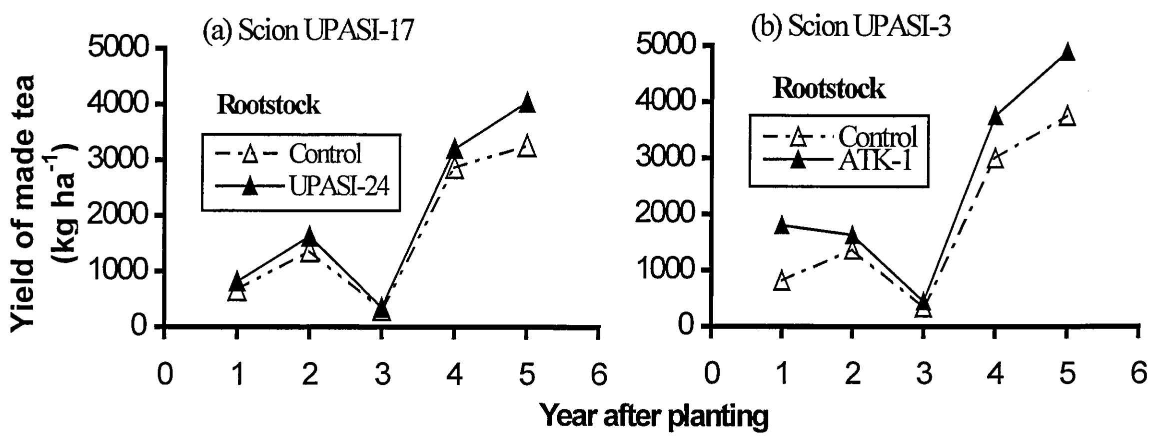


Figure 6: Yields of made tea from (a) scion UPASI-17and (b) scion UPASI-3 grafted onto rootstock clones UPASI-24 and ATK-1 respectively with year (January 1983 to December 1987) after planting. Control refers to the ungrafted scion. The plants were planted in the field in 1979 and pruned in May 1985. In year three (1985) from planting the yield was recorded for four months then the bushes were pruned). The experiment was conducted at UPASI, India. Redrawn from UPASI (1983; 1984; 1985; 1986; 1987).

COMMERCIAL USE OF COMPOSITE TEA PLANTS

Nyirenda (1995) reported that benefits of using composite plants in tea production have been well appreciated by the tea industry in Malawi. Similarly, in Kenya (Corley, 1999) composite tea plants are planted at a commercial scale by Brooke bond Kenya Limited. However, the area being planted with composites is still low. For example in Malawi, Zimbabwe and South Africa areas under composite tea plants are only 82, 18 and 1.6 ha respectively by 1998 (Martin, 1998). The problems associated with the technique of producing composite plants (Nyirenda, 1995) and lack of sufficient planting materials of desirable attributes have limited the rate of adoption. Martin (1998) supported this view and reported that the area under composite tea is small in Malawi due to the technical difficulties estates have in producing composite tea plants and shortages of most recent rootstock and scion materials. Tea growers feel that the technique is labour intensive and requires skill, the cost of grafting is high, while the success rate is low. This is contrary to the findings by Nyirenda (1995) and Nyirenda and Mphangwe (2000) who reported that higher success rate (over 98%) of grafted plants can be achieved under estate conditions. However, it is important to look for possible means of raising labour productivity. Nyirenda (1995) found that one person can only graft 420 unrooted cuttings (using cleft grafting) a day while one person can make 1,250 ungrafted cuttings.

GENERAL DISCUSSION

The research work on composite tea plants done in Malawi, Kenya and India provided useful information on the potential of composite tea plants in tea production. Although there are other benefits, yield and drought tolerance are the major benefits of using composite plants reported in the literature.

Yield

The results of the composite tea plant experiments reported in the literature are inconsistent, and are therefore difficult to interpret usefully. For example, while some composite plants continue to out-yield their respective ungrafted scions for fifteen years in Malawi (Figure 4 a), and five years in India (Figure 6), in Kenya, mixed results were reported. While at the Tea Research Foundation of Kenya (Figure 5) none of the rootstocks improved the yields of the scions, at Brooke Bond Kenya Limited some rootstocks improved the yields of the clones used as scions. All these variations confirm that the effects of rootstock on the growth and yield depend on the scion used. These inconsistent results therefore are mainly caused by lack of common criteria for selecting rootstock/scion combinations. Due to lack of knowledge on how the rootstocks influence the growth and yield of the scions, researchers have not been able to define criteria for selecting scions and match them to the appropriate rootstocks. Other reasons might be differences in management of the experiments, plucking standards, and climate and its day-to-day weather conditions and other environmental related factors. Plant genotypes are known to respond differently at different localities due to variations in environmental factors (Seurei, 1996). Similar results were reported by Ng'etich *et al*. (2001) in their work on genotype x environment interactions on tea in Kenya, who found significant interactions between clones and sites. Yields varied between sites with the lower altitudes producing larger yields than the higher altitudes. This makes it difficult to compare results from different tea growing areas. Nevertheless, the previous studies have indicated that composite tea plants have potential in tea production.

Drought tolerance

The performance of composite tea plants during dry seasons is another benefit reported in the literature. There is evidence that composite tea plants can increase the drought tolerance and therefore the yield during dry season of some tea clones used as scions. For example, in Sri Lanka (Pallemulla *et al*., 1992) found that scion clones TRI 2023 and TRI 2026 grafted onto rootstocks CY9 and DN respectively yielded higher than their respective ungrafted scions even during periods of moisture stress. In Kenya (Bore, 1997) the experience of the 1996/97 severe drought exposed the potential of some rootstocks to improve the drought tolerance of the clones used as scions. Likewise (Corley, 1992), based on field observations during the dry season reported that there were clear differences in severity of drought symptoms between graft combinations and also between graft combinations and their respective ungrafted scions. For instance, clone 152 on its own roots was worst affected as compared to when grafted onto rootstock TN14/3. Similarly, in Malawi (Nyirenda, 1995) the experience of the 1991/92 drought has revealed that composite plants may tolerate and survive drought better than their respective ungrafted plants.

Quality

Kayange *et al.* (1981) evaluated the quality of composite plants by analysing the theaflavin (TF) content of the made tea. The results showed that there were no differences on the quality of made tea between the grafted plants and their respective ungrafted scion. Therefore it was concluded that rootstocks have no significant effect on the quality of made tea of the scions. Bore *et al.* (1995) supported this view and found that the plain tea quality parameters of the individual clones were not significantly affected by grafting on different rootstocks. The increase in yields of the grafted plants are due to the increase in shoot numbers and the increase in shoot numbers is unlikely to affect tea quality (Kayange *et al*., 1981; Pool and Nyirenda, 1981). However, in evaluating the effects of rootstocks on the quality of made tea one should always consider the variations due to shoot growth rates and other management practices, such as nitrogen level (Hilton *et al*., 1973; Kayange *et al*., 1981), which were found to affect tea quality.

Self-grafting

The results from grafting tea clones on their own rootstocks illustrate another inconsistency found in the literature. In Malawi (TRFCA, 1978), grafting tea clones onto their own roots gave no yield benefit, but in Kenya and India mixed results were reported (Satyanarayana *et al*., 1991; TRFK, 1997; UPASI, 1992). For example, in India, while grafting clone UPASI-8 and UPASI-17 on its own roots increased yield, the yield of clone UPASI-3 decreased when grafted onto its own roots (Satyanarayana *et al*., 1991). From these results it is difficult to draw firm conclusions, but it seems there are no benefits of grafting tea clones on their own roots. It is difficult to believe that grafting tea clones on their own roots increases or decreases yields. Genetically there is no difference between the rootstock and the scion, and therefore there should be no difference between grafted and ungrafted plants. The only difference is the existence of scar at the graft union. If this is true that grafting tea clones on their own roots increases or decreases yield, one could conclude that the graft union, particularly the movement of materials through the union, brings about the observed differences. Therefore, apart from understanding how the rootstocks affect the growth and yield of the scions, the knowledge of how the graft unions play a part is equally important.

Mechanisms

In general the primary objectives of most of the previous experimental work on composite tea plants were to increase attributes such as yield or quality and drought resistance. Researchers have put most effort on achieving these objectives, while very little emphasis seems to have been made to explain the mechanisms. Kayange *et al.* (1981) and Nyirenda (1987) supported this view and found that very little work has been done to describe the influence of rootstock on the yield and quality of the scion. Webster (1995a) reported similar observations in fruit crops, where despite the long history of composite plants usage in fruit trees, and numerous studies on the influence of rootstocks on scions growth, researchers are still largely ignorant of how rootstocks bring about these effects. Several theories on rootstock mechanisms were developed. For example in fruit trees Webster (1995a) reported that most of the theories to understand and explain rootstock effects on scion growth suggest that the rootstock and/or interstock, and in particular their union(s) with the scion, bring about their effects upon the scion by influencing:

1. the amounts and/or ratios of promoting and inhibiting endogenous hormones (e.g. ABA) circulating within the tree, particularly between the root system and the aerial tree parts;
2. the movements of assimilates (e.g. sugars and amino acids) or mineral elements between the scion and rootstock; and
3. the amounts of water taken up and moved through the rootstock/interstock, to the scion.

It is argued that it is differences in rootstock effect upon one or more of these processes, which account for their observed differential effects upon scion growth and yield.

In tea, Nyirenda and Kayange (1984) reported that strong interrelationships exist between stem circumference, number of branches and yield. High yielding graft combinations produced plants with thicker stems than the ungrafted scions only on the vigorous rootstocks, whereas weak rootstocks exerted negative effects on growth. An increase in shoot population density was reported to be the main effect of rootstock on the yield of the scion (Kayange *et al*., 1981; Pool and Nyirenda, 1981). Similar findings were reported in grapevines (Zelleke and Kliewer, 1979) where rootstocks had a significant influence on the number of buds broken on the scions.

The drought tolerance of some grafted plants has been reported in the literature to increase as compared to their respective ungrafted scions. Nyirenda (1990) determined root depth of composite plants planted in hessian-sleeved bags (340 mm in diameter and 700 mm deep). From this work he concluded that clones with deep root systems could be selected as rootstocks. This is because of the capacity of their roots to grow vigorously and explore a large volume of soil. This means that the root systems have access to more water and nutrients to allow the plant to grow. These rootstocks can improve the drought tolerance of the clones used as scions, if the roots of these scions when planted ungrafted have not the capacity to grow that much deeper. In fruit trees

Beakbane and Thompson (1939, cited by Webster, 1995), found that difference in root distribution may affect water and mineral uptake and hormone synthesis. Similarly, differences in root and stem (shank or interstock) anatomy many affect the translocation efficiency of water, minerals, or more complex molecules (carbohydrate and plant hormones) in the xylem and phloem. These could be among the reasons for the observed differences in drought tolerance between the grafted plants and their respective ungrafted scions.

Generally the results from the previous experiments on composite plants suggest that there are two main factors that need to be considered in selecting rootstock/scion combinations namely: internal and external factors. The internal factors are those related to the genetic make up of the cultivars. This means that the growth of a composite plant and the improvement of the expected attributes depend on the genetic make up of a rootstock and a scion. For example, in absence of others factors, there is a greater chance for a rootstock to increase the yield of a scion clone which is genetically low yielding than a higher yield scion clone.

The external factors are those mainly related to the growing environmental conditions such as climate and day-to-day weather conditions, soils, altitude, and pests and diseases. A clone that is affected by the environmental factor (s) can benefit from being grafted onto a rootstock which would improve its performance under such growing environments. These internal and external factors seem to play a major role in a composite plant and therefore need to be considered in defining selection criteria.

CONCLUSIONS

The primary objectives of most of the previous experimental work on composite plants not only on tea, but also on other woody crops were to improve attributes such as yield and/or quality and drought resistance. Very little emphasis seems to have been made to explain the mechanisms. It is still not known how rootstocks bring about their effect upon the scions.

Apart from the inconsistency of results and the existence of graft incompatibility of some rootstock/scion combinations reported in the literature, there is evidence that composite tea plants have potential in tea production. However, the adoption of composite plants by the tea industry is limited by problems associated with technical difficulties in producing composite plants. Similarly, lack of clearly defined criteria for selecting scions and matching them to appropriate rootstocks limits the efficient use of composite plants.

Assessment of composite tea plants should take into consideration not only the yield in the first years but also yield over relatively longer period of time. Apart from yield other factors such as climate and environmental effects, success in the nursery and survival of the grafted plants in the field should be considered.

High success rates (up to 98%) of grafted tea plants in the nursery can be achieved if the appropriate method of grafting is applied to the correct rootstock/scion combinations under proper nursery management practices.

Cleft grafting and chip budding have been the most promising and widely used methods of grafting in many tea growing areas.

Recommendations on suitable rootstocks and scions have been made in several countries, as a result of research on composite tea plants.

CHAPTER 3

METHODOLOGY

INTRODUCTION

The experimental work was carried out in the Southern Highlands of Tanzania, which is the main tea growing region of the country. This chapter describes the climate and the weather conditions as well as the soils of the site, the experimental details and the statistical analysis of the data. The chapter gives the general methodology of the study and provides a link with other chapters where the specific methodologies are dealt with.

CLIMATE AND WEATHER

The experiment was sited at Ngwazi Tea Research Station (latitude 8°32' S, longitude 35°10' E, altitude 1840 m) in the Mufindi District of the Southern Highlands of Tanzania. The climate of the site can be divided into three main seasons (Stephens and Carr, 1991b). From June to August is cool and dry (mean temperatures 13 – 16 °C). During this time, shoot growth and therefore tea yields are mainly limited by low temperatures and water stress, although the former dominates (TRIT, 1999). From September to November is dry but warm (mean temperatures 16 - 19 °C), during which yields of unirrigated tea is limited by the poor availability of soil moisture. This is followed by the warm-wet season (December to May). This is the main crop season during which most of the tea in the Southern Highlands of Tanzania is harvested. In this period, both temperatures and soil moisture status favour shoot growth. The mean annual rainfall at the site is in the range 880 - 1000 mm in six years out of ten. Figure 7 summarises the observed weather conditions, for the period 1989 to 2000, for the most important climatic variables, affecting the growth and yield of tea.

During 1996 (when the experiment was started) to 2000 daily weather data were recorded from a meteorological weather station sited on well-watered short grass. Maximum, minimum, dry and wet bulb air temperatures were recorded at 09.00 h. Mercury in glass and alcohol in glass thermometers were used to measure the maximum and minimum air temperatures respectively. Unaspirated mercury in glass, both for dry and wet bulb thermometers were used to determine the vapour pressure and saturation deficit. Dry and wet bulb temperatures were also recorded at 15.00 h in order to calculate the mid-afternoon saturation deficit (kPa). Rainfall (mm d^{-1}) was measured using a standard cylindrical 127 mm diameter gauge with its receiving surface about 300 mm above ground level.

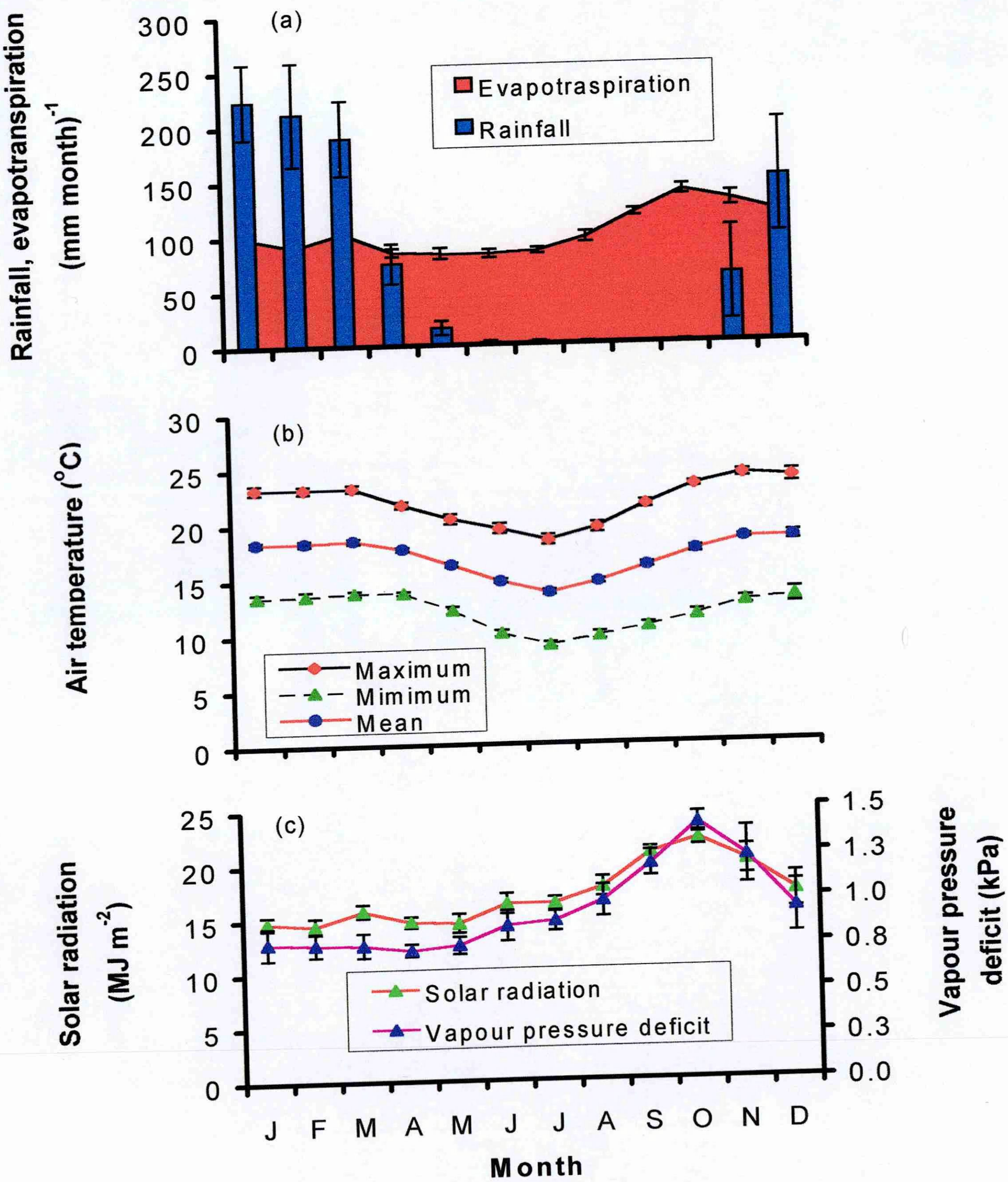


Figure 7: Monthly (a) total rainfall and potential evapotranspiration (measured using sunken evaporation pan, 1.83 x 1.83 m), (b) mean temperatures and (c) mean solar radiation and saturation deficit at 15.00 h at Ngwazi Tea Research Station (lat. 8°32′ S, long. 35°10′ E, altitude 1840 m, for the period 1989 to 2000. Error bars indicate 95% confidence interval of the mean for each monthly value; n=12.

Daily evaporation (ET_{pan} mm d^{-1}) was measured using screened, sunken 1.83 x 1.83 m British square evaporation pan. A Gunn Bellani pyranometer was used to measure total daily shortwave solar radiation (MJ m^{-2} d^{-1}). The wind-run (km d^{-1}) was recorded at 09.00 h with a 2 m high anemometer linked to a trip counter. To calculate the daytime wind speed (m s^{-1}), the wind-run was measured again at 15.00 h each day.

SOILS

The soils in Ngwazi area are acidic (pH 4.5 - 5.5) Xanthic ferralsols with the texture of sandy clay above 0.15 m and of clay below (Baillie and Burton, 1993; Burgess, 1992b; Marcelino, 1996). The soils are highly weathered, deep, well-drained and of medium texture. A detailed chemical analysis of soil samples collected about 500 m from the experimental site and nutrient status of soil samples collected adjacent to the experiment are reported by Kigalu (1997). At field capacity (-10 kPa), the volumetric water content of the soil in the top 0.15 m is 24.7%, which increased to 32.5% at a depth of 1.8 m (Burgess, 1992b). Figure 8 shows the water release curve of the soils at Ngwazi Tea Research Station.

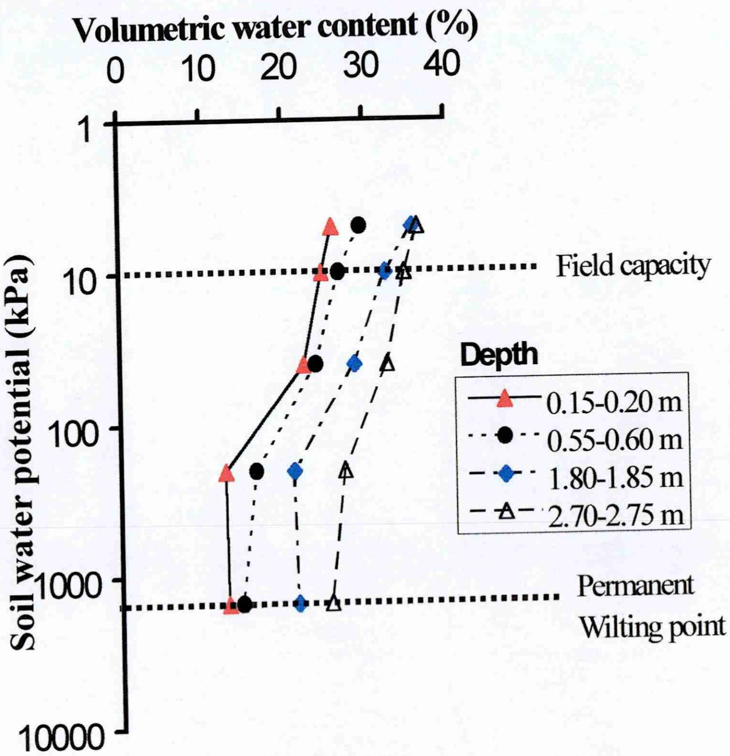


Figure 8: Water release curve for soil at Ngwazi Tea Research Station. Soil samples were taken at about 500 m from the experimental site. Redrawn from Burgess (1992).

The experiment was established on land belonging to Brooke Bond Tanzania Limited's Ngwazi Estate. Before planning, the experiment the land was ploughed by the estate. Prior to the development of the irrigated tea at Ngwazi the land was used for maize cultivation and cattle ranching and the pH of the soils of some of the fields within the estate, including the experimental site was high. For that reason, applying elementary Sulphur to lower the pH was a common practice during land preparation. Two applications of elementary Sulphur were applied in the experimental site. Unfortunately, there were no records on the rates of applications as well as the soil pH before the application. However, immediately after planting measurements of soil pH within the experimental plots at 0 - 0.5 m deep indicated that the pH ranged between 4.7 and 4.9, which is within the acceptable range for tea (Othieno, 1992).

EXPERIMENTAL DETAILS

Grafting methods

A number of grafting methods have been used in different tea growing areas (see Chapter 2) but cleft grafting and chip budding are the most commonly used. The choice of grafting method appears to be a matter of preference, as there are no clear guidelines reported in the literature to enable tea growers to select the method. In this study, cleft grafting was selected primarily due to the fact that this was the method preferred and used by some of the commercial companies in East Africa.

Graft combinations

Six clones (labelled, SFS150, 6/8, PC81, clone 1, 207* and TN14/3) and two clones (labelled S15/10 and K35**) were selected as rootstocks and scions respectively. The initial plan was to include a wide range of proven or semi-proven rootstocks (e.g. PC87 and MFS87 from Malawi). Unfortunately, at the time when the experiment was started, cuttings of these rootstocks were not available. For that reason the choice of the rootstocks was limited to the clonal material available locally. The scion clones selected are commercially important clones in East Africa. Both clones have large leaves with

** Also known as BBT207 (Carr, 1995).*
*** Other names are BBK35 (Smith and Bayliss, 1994), BB35 (Ng'etich and Stephens, 2001)*

soft and long internodes, which grow clear of the older leaves, and therefore easy to pluck by hand. While clone S15/10 is high yielding clone (Oyamo, 1992), clone K35 is a good quality clone (Carr, 1995; Ng'etich *et al*., 1995). Both clones however, are drought susceptible (Burgess, 1992b; Ng'etich *et al*., 1995). It was anticipated that grafting these clones onto a rootstock might improve its drought resistance and yields during the dry season. Table 2 summarises some of the available information of the clones used as rootstocks and scions.

Table 2: Summary of available information, origin, areas growing in Tanzania, maximum yield, quality, drought tolerance and base temperature for shoot development and extension for clones used as (a) rootstock and (b) scions.

(a)

	Rootstock					
Category	SFS150	PC81	6/8	TN14/3	207	Clone 1
Selected in	Malawi	Malawi	Kenya	Kenya	Tanzania	Tanzania
Area covered (ha)	Unknown	260[14]	550[14]	100[14]	470[14]	Unknown
Maximum yield (kg ha^{-1})	8,000[15]	Unknown	6,000[5]	5,000[3]	7,000[2]	4,000[2]
Quality	Average[13]	Good/ Average[1]	High[11]	Plain[3]	Average[4]	Unknown
Drought tolerance	Good[6]	Good[13]	Susceptible	Unknown	Susceptible	Good[5]
Base temperature (°C):						
For shoot extension	7 [5]	Unknown	10 [7]	7 [9]	8.6 [5]	12.8-14.5 [10]
For shoot development	7.7 [5]		14.9 [8]		11.6 [5]	13.9[5]

(b)

	Scion	
Category	S15/10	K35
Selected in	Kenya	Kenya
Leaf size	Large	Large
Area covered (ha)*	280[14]	130[14]
Maximum yield (kg ha^{-1})	11,000[11]	6,000[5]
Quality	Plain[11]	High[4]
Ease in plucking	Easy[3]	Easy[3]
Drought tolerance	Susceptible[5]	Susceptible[5]
Base temperature (°C):		
For shoot extension	9[5]	11.4 [5]
For shoo development	7.6[12]	14.8 [5]

[1]Nyirenda, 1996 ; [2]Nixon, 1996; [3]Ng'etich *et al.*, 1995; [4]Carr, 1995; [5]Burgess, 1992; [6]Nyirenda and Grice, 1990; [7]Stephens and Carr, 1993; [8]Smith *et al.*, 1990 ; [9]Obago *et al.*, 1988; [10]Stephens and Carr, 1990; [11]Owour, 1990; [12]Squire *et al.*, 1993; [13]TRFCA, 1990; [14]Kimambo, 2000; [15]TRFCA, 1995.

Cuttings were collected from Brooke Bond Tanzania Limited's estates. All procedures for preparing bushes (known as mother bushes) for cuttings were carried out using standard commercial practices. Mother bushes were pruned at about 25 mm above the previous pruning level. The type of pruning used was a straight cut-across the framework (TRFK, 1986). Cuttings were collected between five and seven months after pruning. Only vigorous cuttings were selected from the mother bushes. Cuttings were wrapped in wet sacking and taken to a shelter near the nursery where they were immediately watered to maintain their turgor prior to grafting.

The two scion clones (S15/10 and K35) were grafted onto each of the six rootstocks (SFS150, 6/8, PC81, clone 1, 207 and TN14/3). Similarly, the scions were grafted onto each other (i.e. S15/10 on K35 and *vice versa*). Cuttings of ungrafted scions were also prepared at the same times as the controls. Cleft grafting (Plate 1) took place in the nursery in November 1994 and again in January/February 1995. The cleft grafting method used is fully described by Kayange (1990) with slight modifications (see below).

Preparation of rootstock

The rootstocks used were unrooted single node cuttings. Both the top and the bottom of the stem of the rootstock cuttings were cut horizontally, rather than sloping cut as suggested by Kayange (1990) and also as normally used for ungrafted cuttings. The top part of the stem was cut about 20 mm above the leaf known as "mother leaf". Then a cleft of about 15 mm was made in the centre of the stem with a sharp razor blade without removing any tissue or damaging the bud or the mother leaf. The cleft was then gently widened by hand to enable the wedge of the scion to fit in (Plate 1 a). The lower part of the rootstock cutting stem was cut 30 to 50 mm below the mother leaf.

Preparation of the scion

The scions consisted of a mother leaf, an axillary bud and 20 mm stem below the mother leaf. A horizontal cut close to the bud was made at the top part of the scion cutting taking care not to damage the bud or the mother leaf. The lower part of the stem was then cut into a wedge 15 mm long to fit into the cleft in the rootstock. For ease of handling (during e.g. planting in the polypots), the wedge of the scion was oriented so that when joined to the rootstock both the mother leaves of the scion and rootstock faced in the same direction (Plate 1 b).

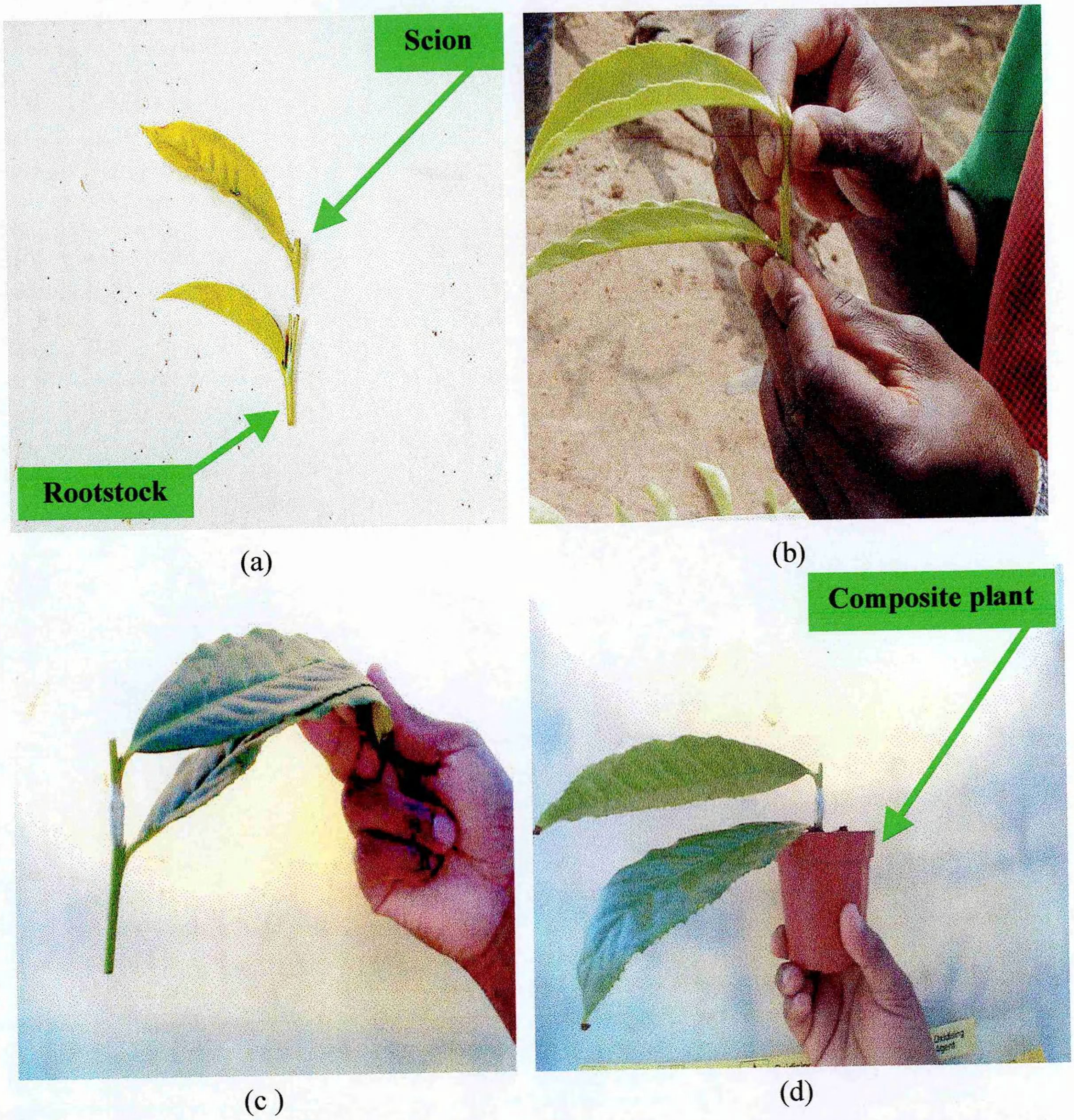


Plate 1: Stages of producing a composite tea plant using cleft grafting (a) preparation of rootstock and scion (b) inserting a scion into a rootstock (c) a tied graft union and (d) composite tea plant planted in a container. The single leaf remaining on each part of the cutting is known as the mother leaf.

After preparation, both the scion and the rootstock were immersed in Bravo solution (Zeneca Agrochemicals) (fungicide) at the recommended concentration to prevent fungi attack. Then each scion was carefully matched with a rootstock cutting to ensure that the cambia on each section were in direct contact. The selected scion was then inserted into the cleft on the rootstock and the wound was tightly wrapped with a polythene strip before potting (Plate 1 c).

The grafting work was done in the nursery belonging to Brooke Bond Tanzania Limited. All the nursery management practices such as soil and polypot preparation, fertilizer application, watering, pest and disease control and shade were the same as those practised by the commercial companies in the Southern Highlands of Tanzania and as described by TRFK (1986). The plants were kept under a polythene tent for about nine months, and then under shade for four months, at which time the polythene strips used to bind the graft were removed.

In September 1995, 9 - 11 months after grafting, the plants were counted to determine the survival rate. The survival rate varied with rootstock/scion combination, ranging from 0 to 93%, the highest being scion clone K35 grafted onto rootstock SFS150 (Table 3). With the exception of rootstock TN14/3, the scion clones S15/10 and K35 grafted onto the other rootstocks and on each other (i.e. S15/10 on K35 and *vice versa*) had mean survival rates of 57 and 61% respectively. The corresponding success rates from the ungrafted scion clones were 95 and 87%.

Table 3: The nursery survival rate counted in September 1995 (9-11 months after grafting). The plants were grafted in November 1994 and January/February 1995. 'Opp' refers to rootstock/scion combination S15/10 on K35 and vice versa. Control is the ungrafted scions.

	Survival rates (%)								
	Rootstock								
Scion	Control	'Opp'	PC81	SFS150	Clone 1	207	6/8	TN14/3	**Mean**
S15/10	95	66	63	65	25	51	72	0	**55**
K35	87	50	75	93	53	38	57	0	**57**
Mean	**91**	**58**	**69**	**79**	**39**	**45**	**65**	**0**	**56**

Generally rootstock clones PC81, SFS150 and 6/8 survived considerably better than the other combinations. Clones 1 and 207 were less successful, whilst grafting the two scions onto rootstock TN14/3 resulted in total failure. Several factors might have caused these differences, including variations in compatibility of the two scions, difficulty in selecting well-matched scion and rootstock cuttings in terms of stem diameter, time of grafting and the inexperience of the grafters. The low success rate of clones 1 and 207 may also have been caused by the fact that they have shorter and thinner internodes than other large leaf clones therefore making it difficult to align the cambia accurately. Clone TN14/3 is widely used as rootstock at a commercial scale in Kenya. The failure of this rootstock was probably due to the use of very young cutting material, which had to be taken from two-year-old plants because there were no other bushes available. Generally, the skills of the grafters appeared to have major impact to the success rate observed, as this was their first or second attempt to graft tea plants. Recent work in Malawi (Nyirenda and Mphangwe, 2000) has shown that a success rate over 85% is possible, as compared to 60% achieved in 1981 (Scarborough, 1981), suggesting that with skilled grafters, it is possible to achieve a high success rate.

In February 1996, 13-15 months after grafting, the plants were planted out in the field at a spacing of 1.2 x 0.8 m. Because of the total failure of rootstock TN14/3 and poor success rates with the rootstocks of clones 1 and 207, only combinations of rootstocks SFS150, PC81, 6/8 and the opposing grafting (i.e. S15/10 on K35 and *vice versa*), together with the ungrafted scions were planted in the main experiment. The experiment was intended to have four replicates, but the poor success rate obtained in the nursery meant that there were only enough plants for two replicates.

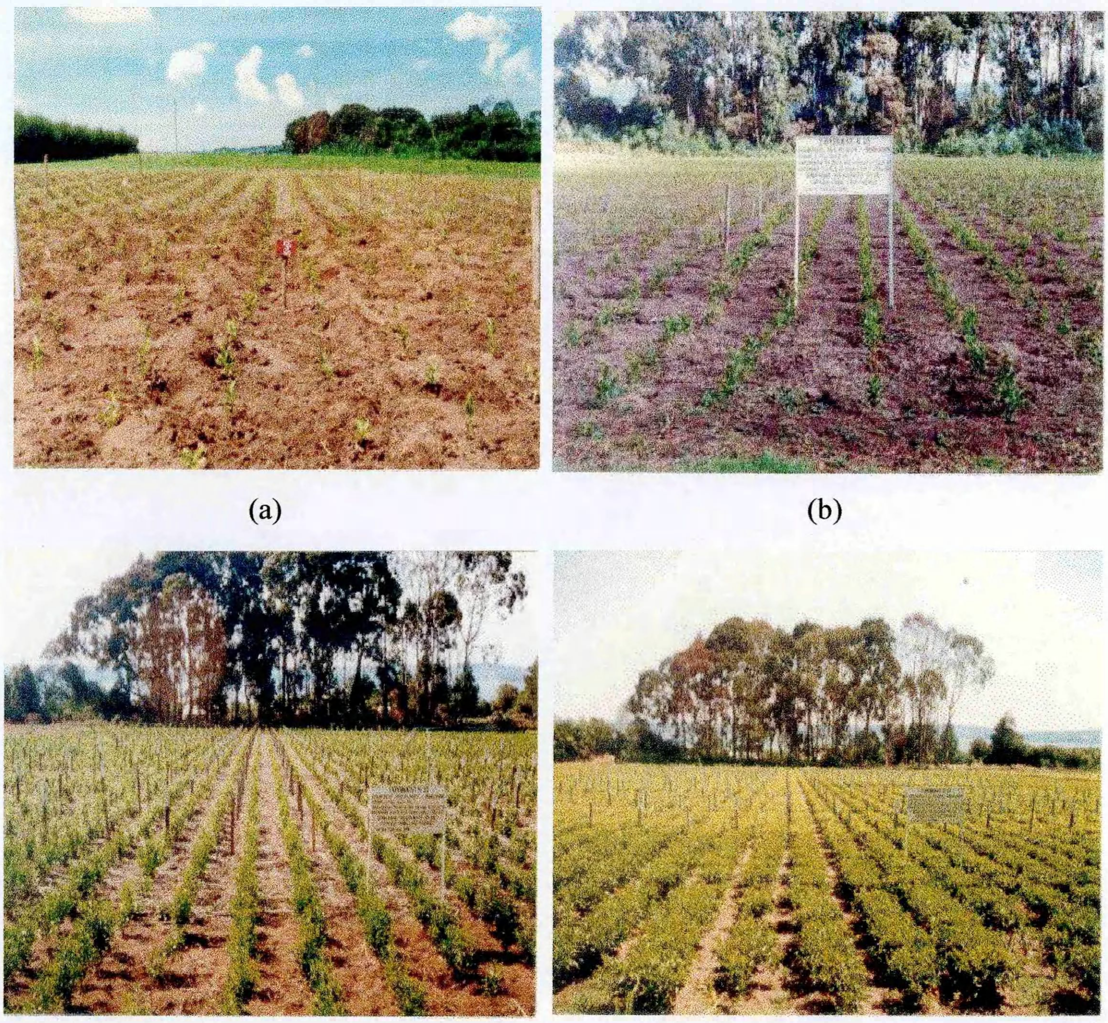
Two combinations, scion clones K35 and S15/10 grafted onto rootstock clone 1 and 207 respectively and the ungrafted PC81, were planted adjacent to the trial as observation plots.

Immediately after planting, micro-catchments were dug to minimise the movement of surface runoff between sub-plots, and 'Primagram' was applied as a pre-emergent herbicide at 4-5 litres per hectare (150 millilitres in 20 litres of water). The plants were mulched with napier grass in May 1996. In November 1996, all branches above 0.30 m were cut back (a process known as "de-centering") to promote lateral growth in order to achieve full ground cover quickly. Between December 1996 and May 1997 shoots above 0.5 m in length were removed or "tipped" to produce a level plucking surface.

The first full season of harvest started in June 1997. Shoots were harvested at intervals of two phyllochrons*, which is the currently recommended harvest interval in Tanzania. Harvest dates were estimated using the previously derived linear relations between phyllochron rate (i.e. number of phyllochrons per day) and the daily mean air

* *A 'phyllo-chron' is a Greek word for 'leaf-time', which is the time between a shoot unfurling two leaves (Burgess and Myinga, 1992)*

temperatures (Burgess and Myinga, 1992). The mean phyllocron increment used were derived from clones S15/10 and K35 in another experiment at the same site (Burgess, 1993b).



(a) (b) (c) (d)

Plate 2: View across the experiment in (a) March 1996 (b) July 1996 (c) October 1996 and (d) July 1997, one, five, eight, and eighteen months after field planting respectively.

During 1996 and 1997 fertilizer was applied at rates of 120 and 180 kg N ha^{-1} per annum respectively as a 2:1:2 compound with P_2O_5 and K_2O. These rates were applied in four equal splits in 1996, and three in 1997. From 1998 fertilizer was applied at the rate of 300 kg N ha^{-1} per annum in two (January and July) equal splits. Zinc (4.5 kg ZnO ha^{-1}) was applied annually in three equal applications, but in both 1998/99 and 1999/00 single annual applications of 1.5 kg ZnO ha^{-1} were applied.

The experiment was kept free of weeds by regular hand weeding. Sometimes herbicides were applied at the edges of the experiment.

Design

The experimental design is based on the line-source irrigation layout, which allows continuously variable amounts of water to be applied either side of a central line of sprinklers. There are two blocks of each scion-clone combination which were divided into plots running perpendicular to the line-source, in which the scion-clone combination were randomly allocated. A total of 160 plants were planted at a spacing of 0.8 x 1.2 m in these plots with the outer edge of plants forming a guard row. This makes an effective net plot of 108 plants (103.7 m^2). These scion-clone combination plots were then split into six irrigation treatment** sub-plots (with 18 plants per plot) ranging from fully irrigated (labelled I_5) to rainfed (no irrigation, labelled I_o) (Figure 9). These irrigation treatments were imposed during the dry season using Bauer B90Z sprinklers, with 7 mm range and 3.5 mm spreader nozzles, spaced at 6 m intervals along the line and operated at nozzle pressure 0.2 to 0.3 MPa.

From planting until the end of August 1998, the experiment was uniformly irrigated during the dry season (at a soil water deficit (SWD) of 30 mm in 1996 and 40-50 mm from 1997) to ensure successful crop establishment. Previous work in East Africa has related the potential water use of tea to Penman's estimate of open water evaporation (E_o) as modified by McCulloch (1965) cited by (Burgess, 1994c) multiplied by an empirical crop factor (Kc) (Burgess, 1994c). A crop factor of 0.85 for well watered tea with complete ground cover is generally accepted (Squire and Callander, 1981). Previous experience at Ngwazi Tea Research Station (Stephens and Carr, 1991a) has shown that evaporation from a British pan (1.8 x 1.8 m) follows ET_o closely. Daily pan evaporation figures were therefore used to represent potential evapotranspiration and the SWD was estimated as (Stephens and Carr, 1989):

$$SWD_i = SWD_{i-1} - R_i - I_i + D_i + ET_{oi} \qquad 3.1$$

When $SWD_i < 0$, then $SWD_i = 0$

** *Also referred to as drought treatments, ranging from minimum drought stress (fully irrigated plots, I_5) to maximum drought stress (unirrigated plots, I_0)*

where SWD_{i-1} is the potential soil water deficit of a previous day, R_i is rainfall, I_i is irrigation, ET_{oi} is the potential evapotranspiration and D_i is the drainage (all in mm) on *i*th day. With the exception of drainage (D_i), all other parameters in equation 3.1 can easily be measured.

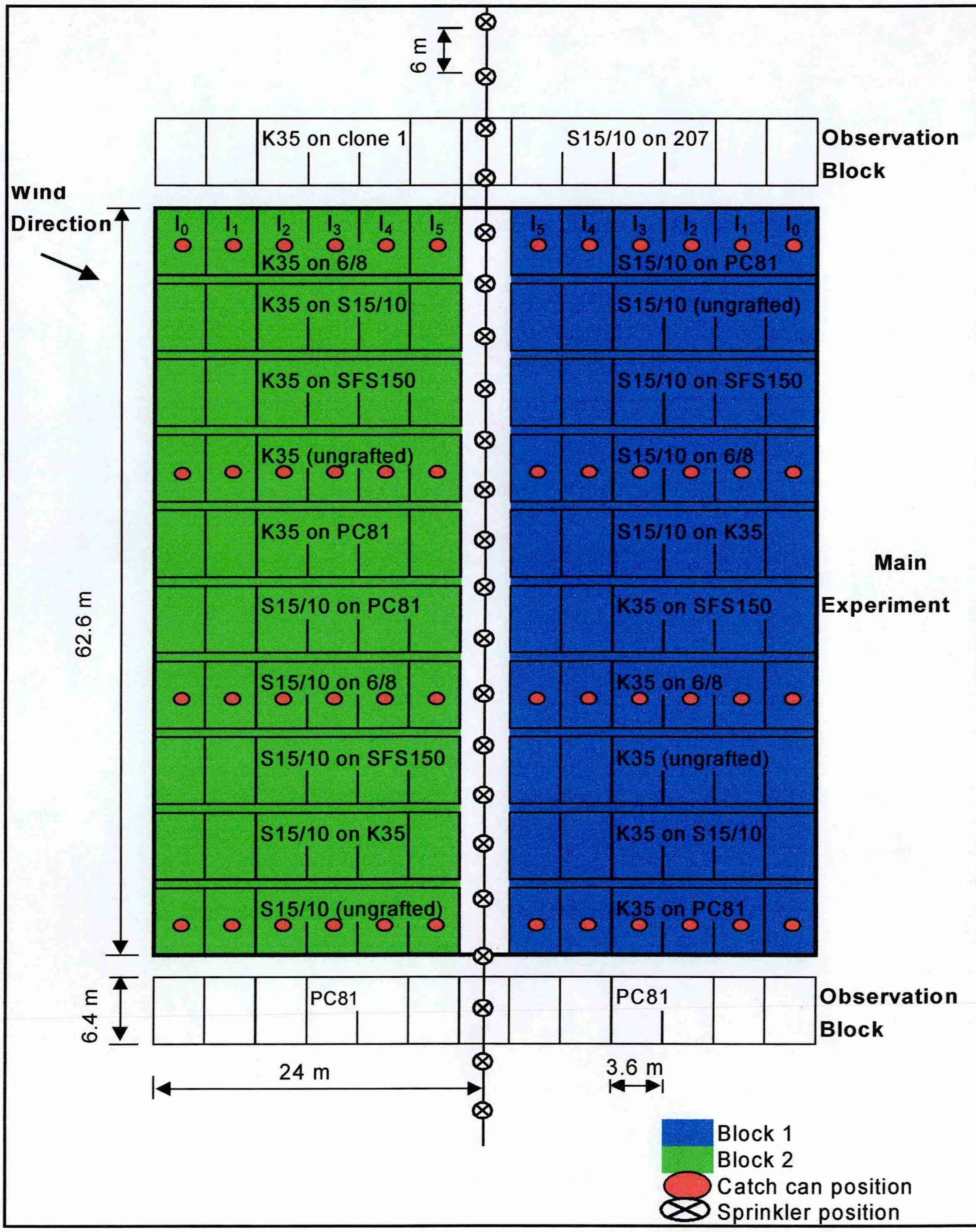


Figure 9: Experimental layout. Where the letters I_0 and I_5 refer to the unirrigated and fully irrigated plots respectively, and I_1 to I_4 are partially irrigated plots in increasing order of the amount of water applied.

At the same site, Stephens and Carr (1991b) assumed the deep drainage under mature fully irrigated tea with complete ground cover was zero once the soil water deficit was larger than zero. To confirm this assumption a CUPPA-Tea (V1.0b) simulation model described by Matthews and Stephens (1996; 1998) was used to predict the amount of water draining through the top 5 m. The model confirmed that deep drainage was negligible during the dry season even for the fully irrigated plots, was therefore assumed to be equal to zero.

The amount of water applied (I_i) in each irrigation treatment was recorded in 48 catch cans spaced systematically across the whole experiment (Figure 9). To determine the change in soil water storage under selected rootstock/scion combinations and irrigation treatments, neutron probe access tubes were installed in July 1999 (details see Chapter 4).

The first differential irrigation treatments were applied in 1998 for about ten weeks between 13 September and 20 November. In the unirrigated plots, the maximum potential soil water deficit reached 400 mm by 20 December 1998, when uniform irrigation was resumed to avoid plant death due to water stress. In 1999/00 dry season, the drought treatments were applied from 24 August to 7 December 1999. The rains started on 12 December 1999 by which time the maximum potential soil water deficit in the unirrigated plots had reached 470 mm. In the 2000/01 season, the differential irrigation applied for about sixteen weeks from 10 July to 26 October 2000. The potential soil water deficit in the unirrigated plots reached 490 mm prior to the start of the rains on 1 November 2000. It was intended to increase the period of water stress in the 2000/01 season as compared to the previous seasons, unfortunately the rains started early than expected. This resulted in the stress experienced by the plants to be about the same as in the 1999/00 season.

STATISTICAL DATA ANALYSIS

Where data were statistically analysed, the statistical package Genstat 5 Release 4.1 (for windows, third edition) developed at Rothamsted Experimental Station, U.K. was used. As proposed by Morgan and Carr (1988) for line-source irrigation layout, analysis of covariance, with distance from the sprinkler line as covariate was carried out. This compensates for any fertility trend running across the experiment, which might be confounded with the irrigation effects. The results were presented as estimates of means as suggested by Riley (2001). The differences between treatments were assumed to be statistically significant at or below 5% level of probability. Appendix A presents a dummy statistical analysis of the experiment.

SUMMARY

The chapter covered the general methodology of the experiment and provides a link with the other chapters where the specific methodologies are dealt with.

The experiment was intended to have four replicates, but the poor success rate obtained in the nursery meant that the plants were enough for two replicates.

The plants were field planted in February 1996 at a spacing of 0.8 x 1.2 m. The first full season of harvest started on June 1997. The harvesting was carried out at an interval of approximately two phyllochrons, which is equivalent to an average of 13 to 17 days during the warm season (September to May) and 22 to 29 days in the cool season (June to August).

CHAPTER 4

WATER USE AND WATER STRESS

INTRODUCTION

Tea grows well under rainfed conditions in areas with minimum annual rainfall of 1,800 mm, with at least 150 mm each month. Areas with annual rainfall below 1,150 mm and/or poor distribution are considered not suitable for tea unless irrigated (Carr and Stephens, 1992). In Tanzania, tea growing areas with adequate rainfall are in bimodal rainfall areas in the North. In the Southern Highlands where most of the national crop is produced, the monomodal rainfall pattern means that the monthly rainfall is less than 150 mm for 3 to 8 months a year.

The current area under tea in Tanzania is about 23,300 ha, of which only about 19% is under irrigation. The remainder is entirely dependent on rainfall, and during the dry season yields of unirrigated tea are limited by drought. Similarly, for some irrigated estates, water availability and/or under-designed irrigation systems result in the amount of water applied being less than the crop demand. Under such conditions, the use of drought tolerant tea cultivars becomes essential for maintaining yields and for survival during long periods of drought. The experiences of severe drought years of 1986/87 and 1991/92 in Malawi (Nyirenda and Mphangwe, 2000) and 1996/97 in Kenya (Bore, 1997) have revealed that some composite tea plants can survive drought better than their respective ungrafted scions. The use of composite tea plants therefore could be one way of producing drought tolerant planting material.

Drought refers to any combination of restricted water as a result of low rainfall or poor soil water storage and/or enhanced rate of water loss (resulting from higher evaporative demand) that tends to reduce plant productivity (Jones, 1992). The latter is mainly controlled by the prevailing day-to-day weather conditions (i.e. saturation deficit, temperature, wind and solar radiation). In most of the tea growing areas in Tanzania, the climate and weather conditions suggest that high evaporative demand is unlikely to cause plant water stress. For example, Tanton (1982) reported a critical saturation deficit of 2.3 kPa above which transpiration is reduced even if there is adequate water in the soil, resulting in restriction in shoot extension. Such deficit however, is rarely reached in most of the tea growing regions in Tanzania (see Table 4 for the experimental site). The insufficient water supply therefore is considered to be the main cause of plant water stress in the study area.

The effects of water stress in plant physiological processes have been reported by many researchers (e.g. Jones, 1992; Davies *et al.*, 1994; Zhang and Davies, 1990; Lovisolo and Schubert, 1998; Lambers *et al.*, 1998). The most obvious effect of water stress is to reduce plant growth due to changes in water potential (i.e. reduction in turgor pressure), which affect cell expansion (Jones, 1992). This limits shoot growth and development and therefore the yields.

The pressure chamber technique has been widely used method for measuring water potential in plants grown under field conditions to quantify the plant water stress (Koide *et al.*, 1989; Turner, 1988). This technique was first used in tea by Carr (1971) and Othieno (1978). Later the technique was successfully used to assess drought stress of clonal tea plants grown under different water regimes in Southern Tanzania (Burgess, 1992b; Nixon, 1996) and rainfed conditions in Kericho (Smith and Bayliss, 1994).

In this chapter, the water use and effects of water stress on composite tea plants are assessed in an attempt to identify drought tolerant rootstock/scion combinations. Similarly, the processes involved are discussed in trying to understand the underlying mechanisms.

METHODOLOGY

During the period of January 1996 to December 2000, daily weather data were recorded as described in chapter 3.

Water use

In July 1999, a total of sixteen neutron probe access tubes, of which twelve were 5 m and four were 2 m long were installed in selected rootstock/scion combinations. The 5 m tubes were installed in the unirrigated plots of each of the two scion clones (S15/10 and K35) grafted onto rootstock 6/8, graft combination S15/10 on K35 and *vice versa*, and in the ungrafted plants of the scion clones. The combinations were selected based on the yield performance observed during the 1998/99 season when the differential irrigation treatments were imposed for the first time. The 2 m access tubes were installed in the fully irrigated plots of the ungrafted plants. Each tube was replicated on either side of the line source. These depths were selected on the basis of the previous work (Stephens and Carr, 1991b) at the same site, which showed that the roots of mature tea bushes can grow at least 5.5 m deep. Similarly, the authors found that there is no water use beyond 2 m in the well-watered plots. Although 5 m deep access tubes were installed in the unirrigated plots, measurements were taken up to 3.1 m, which is the estimated maximum rooting depth of the plants at 42 months after field planting.

Previous work (Burgess, 1992b) did not resolve differences in water use between clones using this technique. Few combinations therefore were selected to quantify the maximum and minimum water use by composite tea plants.

A Wallingford neutron probe (Didcot Instruments Ltd) was used to monitor changes in soil water storage during the dry season. Two sixteen-second neutron probe readings (R_s) were taken at 0.15 m increments to a depth of 2 and 3.1 m in the irrigated and unirrigated plots respectively. A mean of ten standard water counts (R_w) was recorded on each day when the water content was measured in the experiment.

For two dry seasons (1999 and 2000), measurements were taken one to two days before and two to three days after irrigation. Data were collected from 10 August to 11 December in 1999 and from 9 July to 30 October in 2000 dry seasons. During each season, the first measurements (10 August 1999 and 9 July 2000) were taken two days after the last uniform irrigation (prior to imposition of irrigation treatments). The soil was assumed to be at field capacity on these dates.

Neutron probe readings were converted to volumetric water content using a calibration curve (equation 4.2) developed by Kigalu (1997) from readings taken adjacent to the experiment.

$$V_v = 0.73(\text{s.e } 0.10)\frac{R_s}{R_w} - 0.069 \text{ (s.e } 0.05), R2 = 0.68 \text{ (n} = 24) \qquad 4.2$$

Where V_v = volumetric water content, R_s = reading at each plot, and R_w = standard water count.

Calculation of water use

The soil water deficit on each day can be estimated using equation 3.1, described in chapter three, but repeated here for convenience.

$$SWD_i = SWD_{i-1} - R_i - I_i + D_i + ET_{oi} \qquad 3.1$$

When $SWD_i < 0$ then $SWD_i = 0$

Where ET_{oi} is the potential crop evapotranspiration (water use) on *i*th day, R_i and I_i rainfall and irrigation respectively, D_i is the drainage, and SWD_i and SWD_{i-1} are the potential soil water deficits on *i*th day and the preceding day correspondingly (all in mm). During the dry season, deep drainage (D_i) was assumed to be equal to zero for reasons described in chapter 3. Using equation 3.1, the actual crop water use (ETa_i) was then calculated as:

$$ETa_i = SWD_i - SWD_{i-1} + (R_i + I_i) \qquad 4.1$$

Where the term $SWD_i - SWD_{i-1}$ is the change in soil water storage (actual SWD), which is the difference between the sum of water content within the profile on *i*th day and preceding data (i.e. at the beginning and the end of the dry season).

Water stress

Plant water stress was assessed using a pressure chamber (Arimad-2 pressure chamber, ELE International Ltd, Hertfordshire, U.K.). Measurements of xylem water potential were taken from fully (I_5), partially (I_2) irrigated and unirrigated (I_0) plots (i.e. 5 rootstocks x 2 scions x 3 irrigation treatments x 2 replicates = 60 plots). The xylem water potential varies with time of a day (Carr, 1971), so only three irrigation treatments were sampled to minimise the time interval to take measurements between the first and the last plots.

On each occasion, four shoots per plot from the guard rows were sampled. Shoots with two to five leaves and a bud, 90 - 140 mm long were collected. The shoots were cut once and quickly carried to the measuring point (at the centre of the experiment) to minimise the time taken from cutting to measuring (Plate 3), which was within one to two minutes. Each cut shoot was placed in the pressure chamber with its severed end protruding through the gas seal. Using compressed air, the pressure in the chamber was then increased (at 0.005 - 0.02 MPa s^{-1}) until sap appeared at the cut surface. The pressure at which exudation first occurs is considered (Carr, 1971; Koide *et al.*, 1989; Othieno, 1978) to be a direct measure of the shoot xylem water potential in the vascular system of the shoot before it was severed.

(a)

(b)

Plate 3: Measurement of shoot water potential (a) bringing a severed shoot to the measuring point and (b) the measuring point in the centre of the experiment.

Assessment of diurnal changes in xylem water potential by Carr (1971) and Burgess (1992b) showed that the minimum values (i.e. most negative xylem water potential) occur between 12.00 to 15.00 h. Measurements of xylem water potential therefore, were taken within that time of a day on each occasion.

Measurements were taken during 1999 and 2000 dry seasons. Additionally, at the end of the 2000 dry season, plant water stress in the unirrigated plots was also assessed visually. A group of five people walked around the experiment and independently ranked the plots according to the degree of stress. The colour of the leaves and the shoots was used as indicator of water stress. Plants with leaves that looked yellowish and/or defoliated were regarded to be more stressed than those that looked green. The numbers 1, plots with no obvious symptoms of water stress (looked green) to 5, plots showing clear symptoms of water stress (yellowish, scorched and/or defoliated) were used to rank the plots.

RESULTS

During the period of January 1996 to December 2000 the mean annual rainfall recorded (943 mm) was within the range (880 - 1000 mm) experienced in six years out of 10 at Ngwazi. Likewise, the mean air temperature (16.9°C), solar radiation (16.8 MJ m^{-2}) and saturation deficit (0.91 kPa) were close to the long term means (Table 4).

During 1997/98, the experiment was uniformly irrigated. The irrigation treatments were imposed for about ten, fourteen and sixteen weeks in 1998/99, 1999/00 and 2000/01 seasons respectively. The duration of the differential irrigation treatments was determined by the age of the tea to avoid plant death due to water stress in the unirrigated plots. During the differential irrigation applications, the amount of water applied at each plot either side of the line source at every irrigation round was the same for all of the three seasons. Figure 10 shows the pooled mean amount of water applied at each irrigation treatment during the three seasons when differential irrigation was applied.

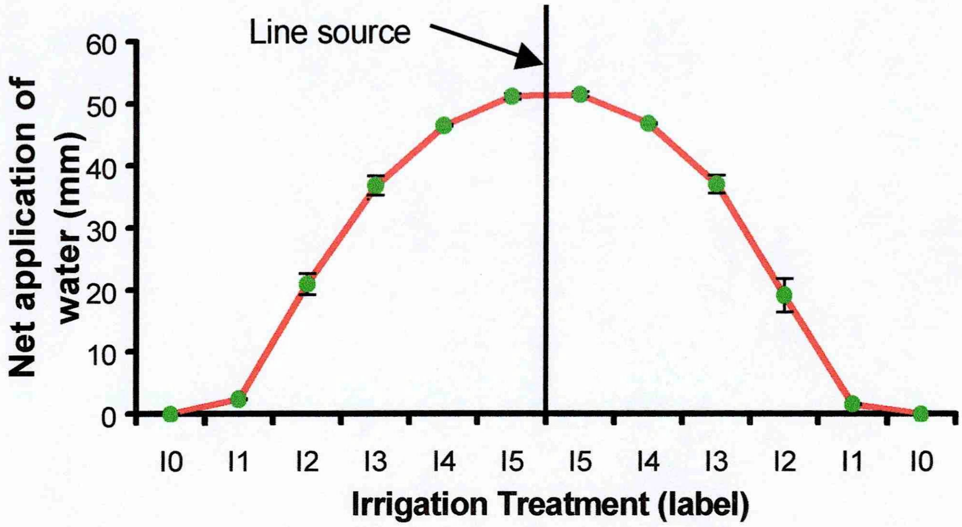


Figure 10: Distribution of mean amount of water during differential irrigation applications to each irrigation treatment either side of the line source during 1998, 1999 and 2000 dry seasons. Error bars show standard error of the mean of each irrigation treatment; n=3.

Table 4: Mean monthly meteorological data for Ngwazi Tea Research Station (lat. 8°32′ S, long. 35°10′ E, altitude 1840 m) for the period 1996 to 2000.

	Monthly				Monthly means of daily values					
	Rain (mm)	Total Etpan (mm)	ETo (mm)	Max SWD (mm)	Max (°C)	Min (°C)	Mean (°C)	Solar Rad'n (MJ m^{-2} d^{-1})	Wind Run (km d^{-1})	VPD 1500 h (kPa)
Jan.	213	106	94		23.5	13.5	18.5	15.3	108	0.87
Feb.	189	93	81		23.5	13.7	18.6	14.7	101	0.72
Mar.	178	111	95		23.4	14.1	18.7	15.8	105	0.81
Apr.	72	87	85	48	21.5	13.8	17.7	13.9	121	0.73
May	16	87	85	120	20.6	11.6	16.1	14.6	117	0.75
June	2	81	79	197	19.2	10.1	14.7	15.4	132	0.77
July	3	85	86	279	18.4	9.0	13.7	16.0	141	0.86
Aug.	1	98	97	374	19.8	9.7	14.7	17.7	139	0.97
Sept.	1	119	111	493	21.6	10.5	16.1	20.5	143	1.13
Oct.	1	136	132	628	22.9	11.2	17.1	21.6	147	1.37
Nov.	77	130	118	716	24.0	12.8	18.4	19.5	133	1.07
Dec	190	118	104	718	23.6	13.1	18.4	16.8	110	0.91
Total	**943**	**1251**	**1167**							
Mean					**21.8**	**11.9**	**16.9**	**16.8**	**125**	**0.91**

N.B.

ET_{pan} refers to evaporation measured directly from a 1.83 m square sunken pan, whilst ETo is calculated using Penman-Monteith equation modified for tea (Burgess, 1994c). SWD is the cumulative maximum potential soil water deficit.

Before the irrigation treatments were imposed, the maximum potential soil water deficit accumulated at each irrigation treatment at the end of the dry season was about 50 mm.

During the 1998/99, 1999/00 and 2000/01 seasons, potential soil water deficits in the unirrigated plots reached 400, 470 and 490 mm respectively at the end of the dry seasons (Figure 11). In the fully irrigated plots, the potential soil water deficits were maintained below 50 mm.

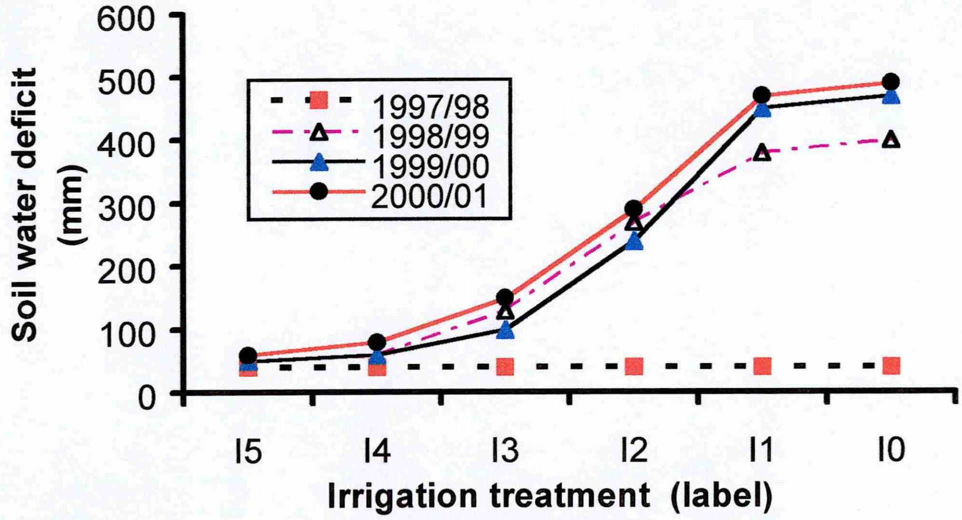


Figure 11: Maximum potential soil water deficit accumulated at each irrigation treatment at the end of 1997/98, 1998/99, 1999/00 and 2000/01 dry seasons. In the 1997/98, the experiment was uniformly irrigated.

Water use

In 1999 and 2000 dry seasons, measurements of water content at field capacity (10 August 1999 and 7 July 2000), prior to the imposition of the irrigation treatments showed that all plots were at the same water content of 31% in the top 0.25 m, which increased to 36% at 3.1 m deep (Figure 12). With the exception of the values at 1.7 m, the moisture contents at field capacity measured in the field were similar to the values determined in the laboratory. By the end of both dry seasons, the water content in the unirrigated plots decreased to about 16% in the top 0.25 m and 31% at 3.1 m deep. In the fully irrigated plots the soil water content at 0.25 and 2 m was about the same (30%), which was higher than in the unirrigated plots at the same depth. During both dry seasons, there were no differences in soil water content between the plots of the two scion clones estimated at the same depth and water regime.

The available water capacity (AWC) between –0.01 and –1.5 MPa soil water potential to a depth of 3.1 m was estimated to be 289 mm. The soil in the unirrigated plots was close to permanent wilting point (about 86% of the AWC was depleted) at the end of both 1999 and 2000 dry seasons. The estimated actual soil water deficits (253 and 241 mm for 1999 and 2000 dry seasons respectively) below scion clones S15/10 and K35 in the unirrigated plots were similar at the end of the dry seasons.

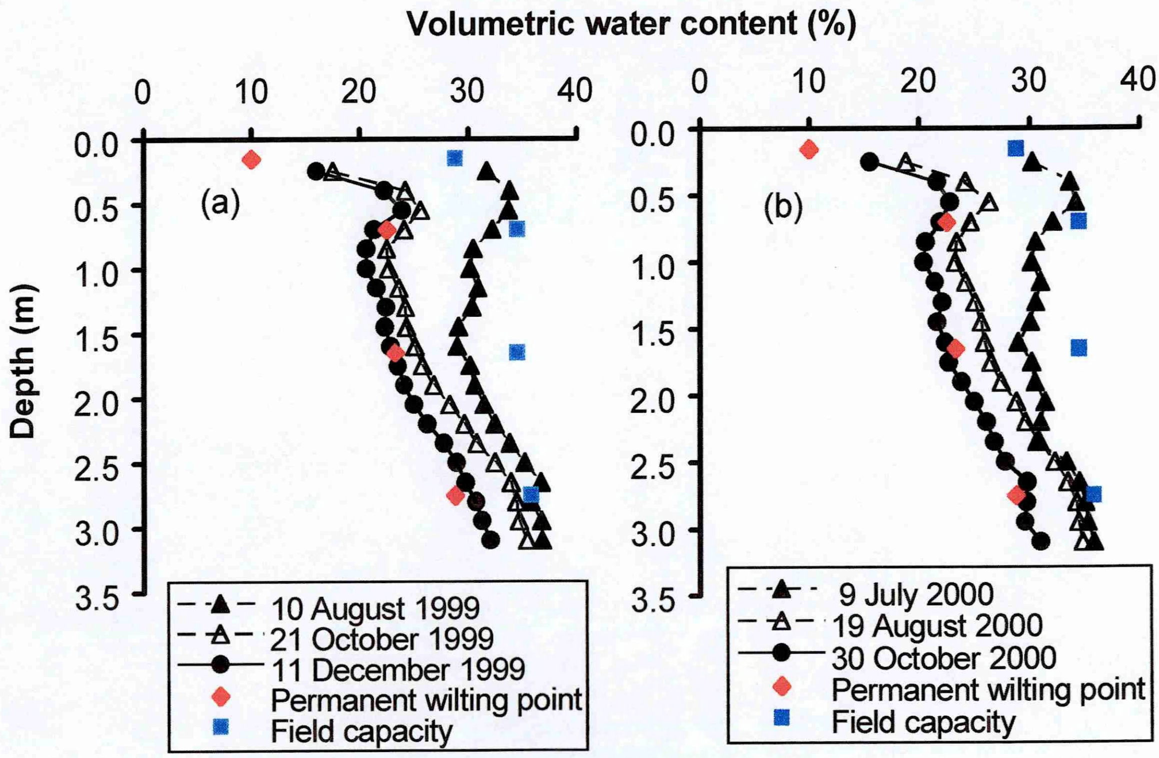


Figure 12: Change in volumetric water content with depth in the unirrigated plots during (a) 1999 and (b) 2000 dry seasons. The water content at field capacity (at –0.01MPa) and permanent wilting point (at –1.5 MPa) are laboratory determined values (Burgess, 1992b).

Comparison of water use when scion clones S15/10 and K35 were grafted onto rootstock 6/8 showed that for the unirrigated plots, there were no significant differences in the amount of water used by the two scions during both dry seasons in the first 3.1 m. Similarly, the water use when the two scions were grafted on each (i.e. S15/10 on K35 and *vice versa*) was the same. In the 1999 dry season, the mean amount of water used (across rootstock treatments) by the grafted plants of scion clones S15/10 and K35 were 470 and 484 mm respectively, which were similar to the corresponding amounts of water (455 and 465 mm) used by the ungrafted plants. The standard error of these estimates was 29 mm (n = 6). In the 2000 dry season, the amount of water used by S15/10 and K35 graft combinations were 345 and 382 mm respectively, compared to 318 and 394 mm used by the ungrafted plants of clone S15/10 and K35. The standard error of the estimates was 23 mm (n = 6). In both 1999 and 2000 dry seasons, although not significant, the grafted plants of scion clone K35 used 3 – 10% more water than those of scion clone S15/10.

Water stress

1999 dry season

During the 1999 dry season, 12 sets of measurements of xylem water potential were taken between 29 September and 11 December 1999. The first measurements were taken when the soil in the unirrigated plots was at an actual soil water deficit of 110 mm (when 38% of the AWC was used) and the last at 253 mm (88% of AWC was used). On each of these occasions, only irrigation and scion had significant effects on the midday xylem water potential. As expected, the xylem water potential for all combinations decreased with increasing SWD. In the driest treatments, the mean xylem water potential decreased from -0.6 MPa on 29 September (actual SWD =110 mm) to -1.9 MPa on 11 December 1999 (actual = 253 mm). Figure 13 summarises the trend of soil water deficit (Figure 13 a) and midday xylem water potential (Figure 13 b & c) for some of the rootstock/scion combinations for the unirrigated plots. Because there were no significant differences in actual SWDs below the unirrigated plots, a pooled mean was used to represent the actual soil water deficit below all rootstock/scion combinations.

Scion clone K35 grafted onto rootstocks PC81 and SFS150 gave a clear trend of xylem water potential with time from the first measurement. While rootstock PC81 consistently gave lower values of xylem water potentials, rootstock SFS150 gave consistently higher values as compared to the other rootstocks. The ungrafted plants of scion clone K35 had intermediate xylem water potentials. The difference in xylem water potential between the two rootstocks decreased as the SWD increased (Figure 13 c). Neither of the two rootstocks however, showed the same trend for scion clone S15/10 (Figure 13 b), although rootstock PC81 did appear to have the lowest xylem water potentials.

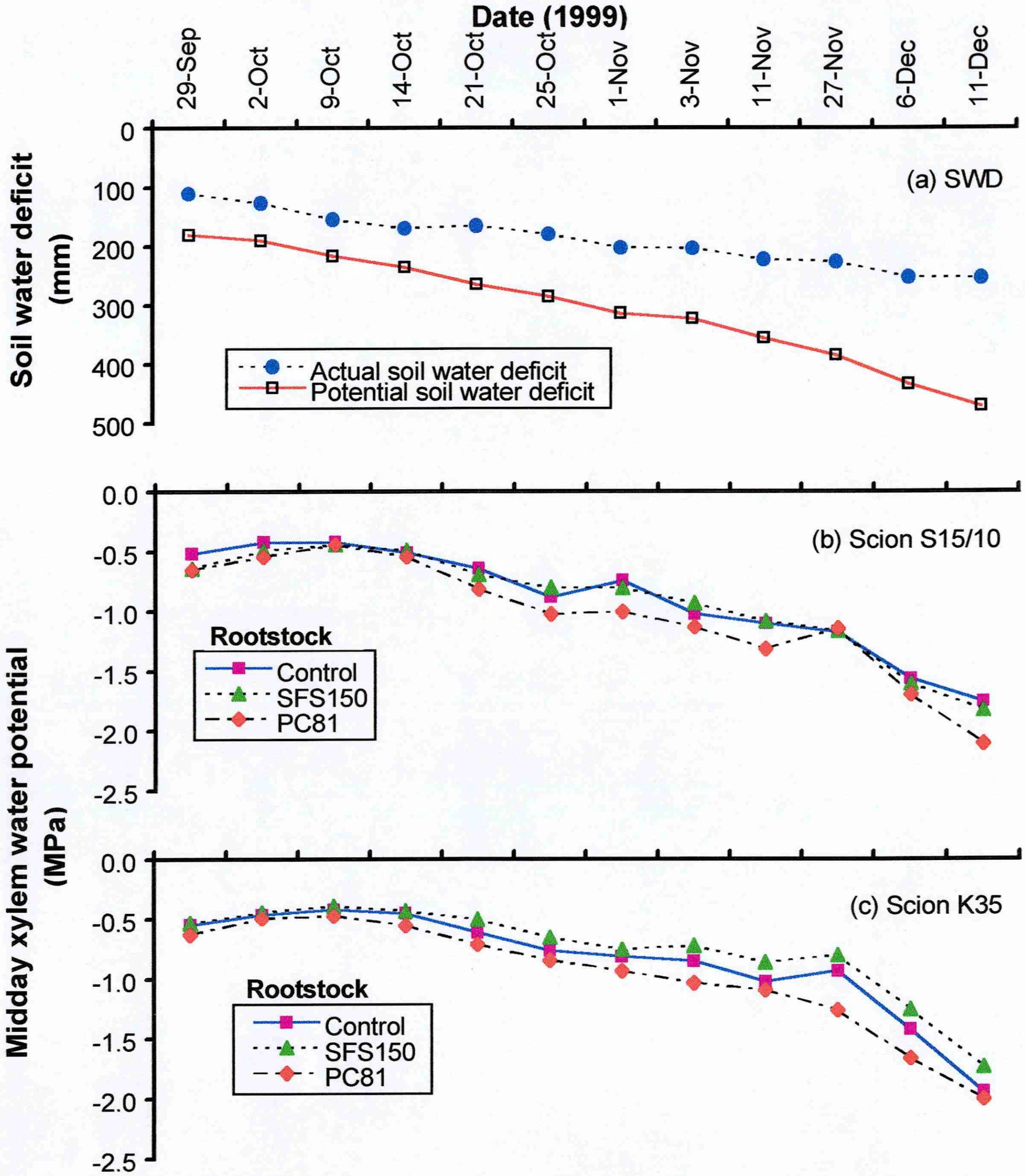


Figure 13: Trend of (a) SWD and midday (1200 to 1500 h) xylem water potential for the unirrigated plots of (b) scion S15/10 and (c) scion K35 grafted onto rootstocks SFS150 and PC81. Control refers to the ungrafted scions. Measurements were taken during the 1999 dry season.

As expected, the midday xylem water potential generally decreased as the SWD increased. Figure 14 presents the effects of actual soil water deficit on the mean (across scion treatments) midday xylem water potential. Although not significant, the mean xylem water potentials on rootstock PC81 were lower than on rootstocks SFS150 and 6/8, particularly as the SWD increased.

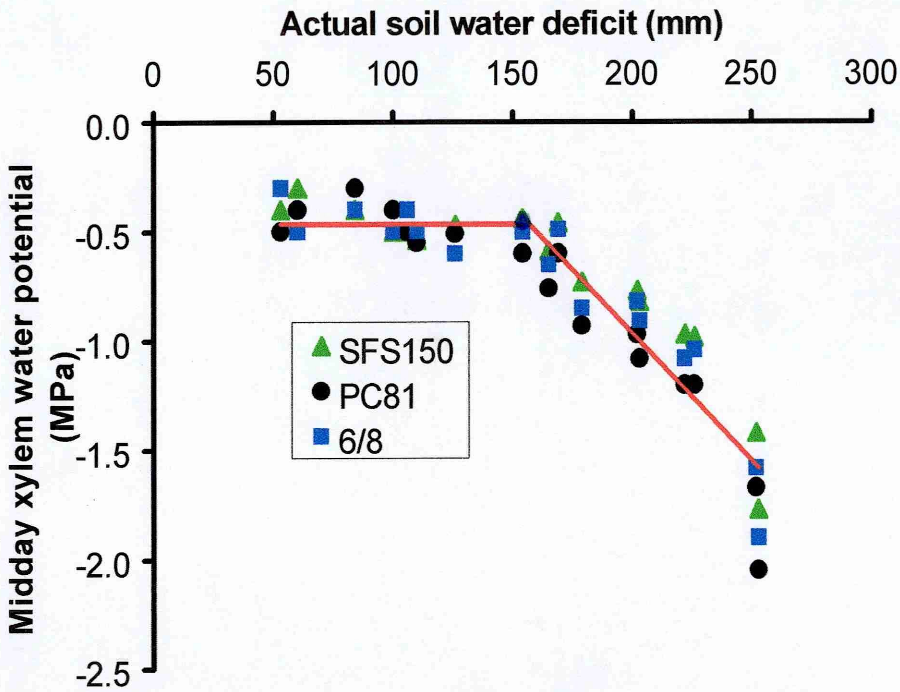


Figure 14: Effects of actual soil water deficit on the mean midday (1200 to 1500 h) xylem water potential of rootstocks SFS150, 6/8 and PC81 (pooled means for scion clones S15/10 and K35). The equation of the sloping line is y = -0.012 (s.e. 0.00014)x +1.35 (s.e. 0.0281). Measurements were taken during 1999 dry season.

The relationship between mean xylem water and actual SWD shows that the water potential remained constant at about -0.5 MPa at SWDs between 0 and 150 mm (when 53% of AWC was depleted), then decreased linearly at a rate of 0.012 MPa $(mm)^{-1}$.

2000 dry season

During the dry season in 2000, xylem water potential measurements were taken between 28 July and 30 October, when the actual SWDs in the unirrigated plots had reached 95 and 241 mm respectively. A total of 14 sets of measurements were taken at different dates. For all treatments, the midday xylem water potentials taken between July and August 2000, when the actual SWD was 95 - 133 mm (33 – 46% of the AWC was depleted), were similar. As in the previous season, from 5 September only scion and irrigation treatments showed consistent effects on the observed midday xylem water potential of the clones used as scions.

Measurements taken on 28 July 2000 when 33% of the AWC was used showed that the xylem water potentials from all treatments were in the range –0.4 to –0.5 MPa. By the end of the dry season (83% of the AWC was used), the xylem water potentials in the unirrigated plots for scion clones K35 and S15/10 had decreased to -1.5 and –1.8 MPa respectively (Figure 15). In the fully irrigated plots however, the xylem water potentials were maintained at about -0.5 MPa.

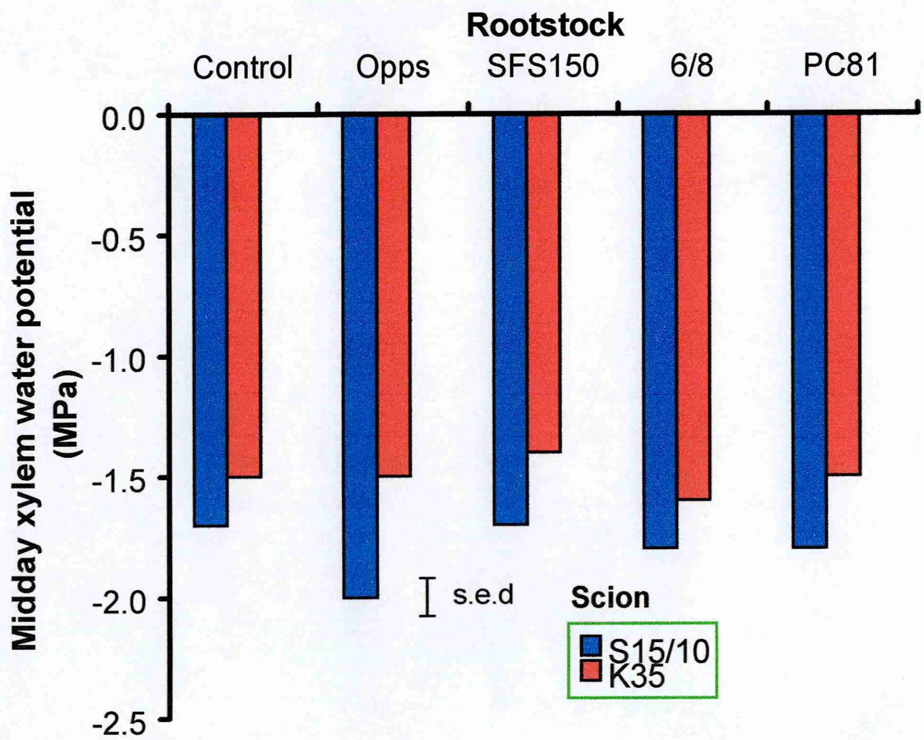


Figure 15: Effects of rootstock on the midday (1200 to 1500 h) xylem water potential of scion clones S15/10 and K35 grafted onto rootstocks SFS150, 6/8 and PC81. 'Opps' refer to rootstock/scion combinations S15/10 on K35 and vice versa. "Control" refers to the ungrafted scions. Measurements were taken on 30 October 2000, actual SWD = 241 mm (when 83% of AWC was used).

The xylem water potential in grafted plants of scion clone S15/10 was in the range –1.7 to -2.0 MPa, compared with -1.7 MPa from the ungrafted plants. The corresponding values for scion clone K35 were in the range –1.4 to –1.6 MPa from the grafted plants and -1.5 MPa from the ungrafted.

The lowest value (-2.0 MPa) of xylem water potential was recorded from scion clone S15/10 grafted onto rootstock K35. In fact visual assessment showed that this combination was one of the most affected by water stress during the 2000 dry season. By contrast, the xylem water potential value (-1.5 MPa) of the opposing grafting (K35 on S15/10) was the same as that of the ungrafted plants of clone K35. Table 5 presents the ranking of the plant water stress (the higher the number the more the symptoms of water stress) in the unirrigated plots at the end of 2000 dry season. Plots of scion clone K35 were ranked 1 to 3 compared with 3 to 5 of clone S15/10. The most stressed plants were those of scion clone S15/10 grafted onto rootstocks PC81, and the least were those of scion clone K35 grafted onto rootstock SFS150.

*Table 5: Ranking of plant water stress (*the higher the number the greater the symptoms of water stress*) at the end of the 2000 dry season. Control refers to the ungrafted scions. 'Opps' refers to the graft combination S15/10 on K35 and vice versa.*

	Rank **Rootstock**				
Scion	SFS150	6/8	PC81	'Opps'	Control
S15/10	3	3	5	4	3
K35	1	2	3	2	2

DISCUSSION

At the end of both 1999 and 2000 dry seasons, the soil down to 3.1 m in the unirrigated plots was close to permanent wilting point (86% of AWC was depleted). As suggested by Gowing and Davies (1989), downward growth of roots is stimulated by soil drying, Figure 12 suggests that the plants survived by extracting water beyond 3.1 m (assuming no deep drainage) towards the end of the dry seasons. Nyirenda (1990) reported similar results, who found that tea bushes with a well developed deep root systems could withstand drought better than those with a shallow root system. The author concluded that rooting depth provides a useful guide when selecting rootstocks. It is useful to note however, that the rooting depth depends on the soil type and therefore may vary with site. Anandacoomaraswamy *et al.* (2000) supported this view, and reported that tea plants with more extensive root systems might have greater transpiration rates because of their greater rate of water extraction from the soil. The duration at which the plants can maintain such transpiration rates however, depends on the amount of water available in the soil (i.e. the AWC). Likewise, canopy leaf area and the prevailing weather conditions (e.g. saturation deficit) are limiting factors to the above argument. Nevertheless, these findings suggest that plant survival during the dry season depends on the rooting volume and the specific root density.

Visual assessment of drought stress during 2000 dry season (Table 5) showed that while plots with clone S15/10 as scion were worst affected by water stress, plots with clone K35 as scion looked green at the end of the dry season (actual SWD = 241 mm, 83% of the AWC was depleted). Similarly, measurements of midday shoot water potential confirmed that scion clone S15/10 was more stressed than K35. Although not significant, the differences in the amount of water used by clone K35 graft combinations, which was more than those used by S15/10 graft combinations could be the reason for the better survival of scion clone K35. This suggests that the choice of the scion influences the response of composites to water stress (i.e. the effects of a rootstock on the water availability to a scion depend on the scion used).

Smith and Bayliss (1994) suggested that the rootstocks influence the water availability to the plant through the root system. The authors did not however, explain what mechanisms are involved in the root system to bring about the observed changes in water availability to the scion. Nevertheless, it appears rootstocks might affect the amount of water extracted from the soil and/or controlling the rate of extraction and movement to the scion. It is also likely that the scions play a major role in the water movement in the plant. As mentioned above, one possible way at which the rootstocks can extract more water from the soil is to increase the volume of soil from which the roots extract water. This can be through increasing the rooting depth and root density.

Root excavation from the fully irrigated plots when the plants under this study were 33 months old showed that the maximum rooting depth of both scion clones S15/10 and K35 grafted onto rootstock SFS150 was the same (2.6 m). Likewise, the maximum rooting depth (1.8 m) of the two scions when grafted onto rootstock PC81was similar. The corresponding rooting depths of the ungrafted plants of scion clones S15/10 and K35 were 2.2 and 1.6 m respectively. Since the rooting depths of both scions grafted onto rootstock SFS150 were the same, but the observed level of drought tolerance of the plants of the two combinations were different, suggests that there are other mechanisms involved. The root measurements however, were collected from the fully irrigated plots when the plants were 33 months old, whilst xylem water potential measurements were taken in the unirrigated plots when the plants were 45 months old. It is likely that the rooting depth and distribution in the two water regimes are different. Nevertheless, it appears the rooting depth and root density are not the only factors determining the water availability to the composite plants. It is likely that other mechanisms are involved in the water uptake and movement through the plants.

The morphology of the root system changes in response to soil drying and varies according to species and soil conditions (Gowing and Davies, 1989). Similarly, Anandacoomaraswamy *et al.* (2000) suggested that differences in the rooting patterns and the canopy leaf area between plants may result in different transpiration rates. In the partially irrigated and the unirrigated plots, it is likely that these attributes for different rootstock/scion combinations changed differently as the SWD increased. For example, leaf defoliation and scorching as an indicator of water stress, which might have reduced the canopy leaf area were observed to vary with rootstock/scion combination (Table 5). These may also affected the rate of water flow in the plants and therefore the way the plants responded to water stress.

Root-to-shoot signalling, which influences the rate of water flow in the plants through control of stomatal conductance could also be one of the possible mechanisms involved. For example, ABA is implicated in inducing root-to-shoot signals in a drying soil (Davies *et al.*, 1994; Gowing and Davies, 1989; Jones, 1992; Zhang and Davies, 1990). The levels of ABA and therefore the root-to-shoot signals probably vary with rootstock/scion combinations, suggesting that these processes might have caused the observed differences in drought tolerance of the plants of scion clones S15/10 and K35.

For scion clone K35, the observed differences in the trend of midday xylem water potential when grafted onto rootstocks SFS150 and PC81 (Figure 13 c) imply that rootstock SFS150 improved the drought tolerance of clone K35, whilst PC81 decreased it. As the rooting depth of the ungrafted plants of clone K35 was less than when grafted onto SFS150, the improved drought tolerance of scion clone K35 by rootstock SFS150 is partly due to increased volume of soil from which the roots extracted water than rootstock PC81. Similarly, rootstock SFS150 had higher root dry weight (and hence root density) in the first 0.5 m than both PC81 and the ungrafted plants of scion clone K35 and S15/10 (unpublished data).

Relationship between xylem water potential and SWD

For scion clone K35, it is interesting to note that the differences in xylem water potential between the two rootstocks (SFS150 and PC81) decreased with increasing SWD. This is primarily due to the difference in the rooting depth of the two rootstocks. The rooting depth of scion clone K35 grafted onto rootstock SFS150 was 2.6 m when the plants were 33 months old compared to 1.8 m at the same age when grafted onto rootstock PC81. The roots of rootstock SFS150 therefore were able to extract water from larger volume of soil than those of PC81. The fact that the differences in xylem water potential between rootstocks SFS150 and PC81 increased as SWD increased implies that the potential of a rootstock to improve the drought tolerance of a scion depends on the duration of the dry period. This point was made earlier by Bore (1997) who reported that the failure of all rootstocks tested at the TRFK to improve yields of the scions was related to the rainfall which meant that SWD large enough to differentiate between rootstocks did not develop.

The relations between SWD and midday xylem water potential (Figure 14) clearly indicates that actual SWDs up to 150 mm, equivalent to soil water potential of -0.04 MPa had no effect on the observed xylem water potential. This was confirmed in 2000 dry season, where all measurements taken between July and August 2000, when the actual SWD was less than 133 mm showed no significant difference between irrigated and unirrigated treatments. Above 150 mm of SWD the xylem water potential decreased steadily at a rate of 0.012 MPa $(mm)^{-1}$. The xylem water potential values observed when the actual SWD was less than 150 mm (potential SWD = 240 mm) were all greater than -0.7 MPa, a critical value reported by Carr (1971) below which tea was becoming sufficiently stressed to reduce yields. This suggests that the xylem water potential values recorded when the actual SWD was below 150 mm would not affect the yields of the scions.

The experience of the previous work at Ngwazi Tea Research Station showed that for young tea (although varying with clone) there is no significant loss of annual yield at potential SWD between 0 and 250 mm (Burgess, 1995; Nixon, 1996; Nixon *et al.*, 2001). On 14 October 1999 when the actual SWD in the driest plots was 150 mm, the potential SWD was 240 mm. It is interesting to note that the optimum potential SWD above which the midday xylem water potential decreased appears to be in the same range as that of yield.

Relations between xylem water potential and actual/potential evapotranspiration ratio

Since the relationship between SWD and xylem water potential described above varies with soil type, it is useful to establish the relationship between xylem water potential and the actual (ETa)/potential evapotranspiration (ETpan) ratio which can be applied in different soil types. A strong linear relationship exists between midday xylem water potential and ETa/ETpan ratio (Figure 16). The ETa/ETpan ratio decreased linearly (at a rate of 0.24 $(MPa)^{-1}$) from about 1.0 when the xylem water potential was -0.5 MPa to 0.7 when the midday xylem water potential reached 1.9 MPa.

Figure 16 suggests that even with small change in the xylem water potential, the actual transpiration rate would be affected well before there was any noticeable effect on other factors such as yield (see Chapter 5). Extrapolating the relationship indicates that when the midday xylem water potential reaches –4.2 MPa, the ETa/ETpan ratio would be zero.

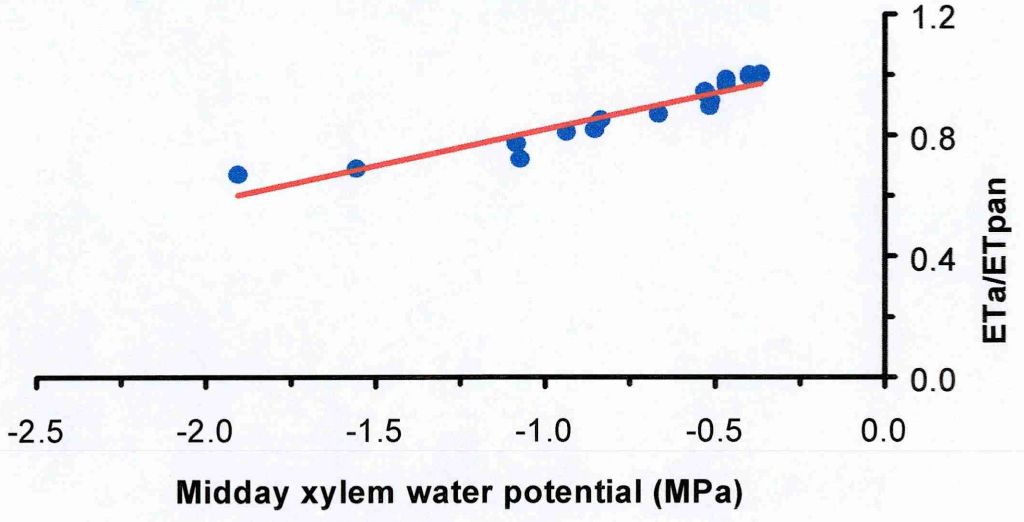


Figure 16: Relationship between midday xylem water potential and ETa/ETpan ratio. The equation of the line is y = 0.24 (s.e. 0.022)x + 1.0(s.e. 0.019); R^2 = 0.89. Measurements were taken during the 1999 dry season.

The assumption underlying the above extrapolation is that the relationship remains linear up to PWP (i.e. when all the AWC is depleted), however, this may not be the case. Previous work in tea (Burgess, 1992b; Carr, 1971; Kigalu, 1997; Nixon, 1996;

Othieno, 1978) did not report xylem water potential values below -2.7 MPa. This was because in all of their studies, measurements of xylem water potential were taken within the range of AWC. It is unclear whether the extrapolated value (- 4.2 MPa) is physically possible or indeed whether the relation between xylem water potential and ETa/ETpan ratio would remain linear up to PWP.

If midday xylem water potential is used to rank the rootstocks in terms of drought tolerance then PC81<6/8<SFS150. Similarly, Figure 15 indicates that rootstock K35 is the most drought susceptible. This ranking compares very well with the visual assessments during the dry season (Table 5), where plots of rootstock SFS150 remained green (although were not flushing), whilst those of rootstocks K35 and PC81 were worst affected by water stress.

CONCLUSIONS

None of the rootstocks tested had a significant effect on either the water use or the midday xylem water potential of the clones used as scions. The choice of the scion however, influenced the response of composites to water stress. (i.e. the effects of a rootstock on the water availability to the scion depend on the scion used). Although it is not clearly understood, root-to-shoot signalling is a possible mechanism, which influenced the amount of water extracted and/or modified the rate of water use by the scions.

On the basis of xylem water potential, the rootstocks appeared to improve the drought tolerance of scion clone K35 more than S15/10. While rootstocks SFS150 and 6/8 appeared to be drought tolerant, rootstocks PC81 and K35 seemed more drought susceptible. This ranking compares very well with visual assessments made during the dry season.

For the Ngwazi soils, actual soil water deficits between 0 and 150 mm (when 53% of AWC was depleted) had no effect on the observed midday xylem water potential. Above 150 mm, the xylem water potential decreases linearly at a rate of 0.012 MPa (mm SWD)$^{-1}$.

A strong linear relationship ($R^2 = 0.89$) exists between midday xylem water potential and ETa/ETpan ratio. The ETa/ETpan ratio decreases linearly at a rate of 0.24 $(MPa)^{-1}$.

CHAPTER 5

YIELD AND YIELD TREND

INTRODUCTION

Improving yields and quality not only in tea but also in many horticultural fruit crops has been the main objective of developing composite plants. In tea, work in Malawi (Nyirenda, 1990; TRFCA, 1995; 1996), India (Satyanarayana *et al.*, 1991; UPASI, 1985) and Kenya (Corley, 1992; Smith and Bayliss, 1994) has clearly demonstrated the potential of some rootstocks to improve the yields of the clones used as scions. In addition, during severe drought periods, composite tea plants survived better than their respective ungrafted plants (Bore, 1997; TRFCA, 1996), which suggests that composite tea plants with these attributes might play a vital role in improving the profitability and sustainability of the tea industry. This has a particular interest for smallholder farmers who rely entirely on rainfall to meet plant water requirements. When severe drought occurs, these farmers can lose a substantial number of tea bushes in their fields. In fact this could be one of the reasons for many gaps found in most of the smallholders' fields. Composite tea plants which can improve yields and are capable of surviving through such adverse drought conditions would be advantageous for tea growers in regions prone to drought.

Previous work on composite tea plants (Barua and Sakia, 1973; Pallemulla *et al.*, 1992; Satyanarayana *et al.*, 1991) has revealed the existence of graft incompatibility between some rootstock/scion combinations, implying that the ability of a rootstock to improve attributes such as yield and drought tolerance of a scion depends on the scion used. The benefits of using composite tea plants therefore, can only be realised when scions are matched to the appropriate rootstocks. In this chapter the yields of composite tea plants grown under different water regimes ranging from fully irrigated to rainfed conditions, as well as the yield development over time, are examined. The yield of made tea depends on the fresh weight of leaves harvested and on their dry matter content. The effects of rootstock on the dry matter content of shoots of different scions are also assessed.

METHODOLOGY

The performance of the composite tea plants in the field was monitored during the first year after planting by counting the number of plants that died in each plot on eight days between 9 February 1996 and 25 January 1997. On each occasion, the dead plants were uprooted and replaced with healthy plants of the same rootstock/scion combination. The development of ground cover as an indicator of field performance was also monitored, initially once a month from December 1996 to May 1999 and then at intervals of three months (see Chapter 7).

Dry matter content of harvested shoots

In order to convert the fresh weight of harvested shoots into dry weight, a conversion factor was derived by determining dry matter content of harvested shoots. Since this varies with clones (Burgess, 1992b) and with seasons (Burgess, 1992c; Cloughley, 1981; Kigalu, 1997), the effects of rootstock, seasonal variation and drought on the dry matter content of harvested shoots of the scions were studied (see Chapter three for the details of the seasons of the year). The dry matter content was determined at alternative harvests from the fully irrigated (I_5) and unirrigated (I_0) plots. These two extreme irrigation treatments were selected in order to determine the effects of drought on the dry matter content. A total of 40 samples (5 rootstocks x 2 scions x 2 irrigation x 2 replicates = 40) were randomly collected from the harvested leaf on each occasion. The samples (each 25 - 80 g) were oven-dried at 80 - 90°C for 24 hours and re-weighed to determine the dry weight, which was then used to derive the conversion factor.

Yield

In commercial practice in Southern Tanzania, young tea bushes are trained to achieve full ground cover quickly by cutting branches above a certain height (a process used to allow earlier harvesting known as "bringing to bearing"). In November 1996, all branches above 0.3 m were removed to promote the growth of wider spreading shoots. Between December 1996 and May 1997 shoots taller than 0.5 m were broken back to that level to produce a level-plucking surface.

Routine harvesting started on 16 June 1997, and continued at intervals of approximately two phyllochrons, calculated from daily measurements of air temperature (Burgess and

Myinga, 1992). The mean phyllocron increment used were derived from clones S15/10 and K35 in another experiment at the same site (Burgess, 1993b). These harvesting intervals are equivalent to an average of 13 to 17 days during the warm season (September to May) and 22 to 29 days in the cool season (June to August). All shoots with at least two leaves and a bud above the plucking surface were removed by hand at each harvest. The fresh weight of harvested shoots from each plot was recorded. This was converted to dry weight using a conversion factor derived from dry matter samples of harvested shoots (see above) collected within the same season of the year. Yield data for four full seasons (1997/98, 1998/99, 1999/00 and 2000/01) together with the first five months of harvest (December 1996 to May 1997) were collected. The crop season was defined as extending from 1 June to 31 May the next year, in order to include all the three main climatic seasons of the year described in chapter three. This enables an assessment of the effect of seasonal changes on the yield of tea.

Unless stated, the yield responses to drought were presented using potential (rather than actual) SWD. This is primarily because the information is directly of commercial value and therefore presented in a way that tea producers can easily understand and quantified. For example, using a simple meteorological station, tea growers can determine the critical potential SWD above which plants are sufficiently stressed to lose annual yields. This allows them to schedule irrigation so that such deficits are not allowed to accumulate. Likewise, using potential SWD allows comparison directly with the previous work (e.g. Stephens and Carr, 1991; Nixon *et al.*, 2001; Burgess, 1995; Carr and Stephens, 1992; Burgess, 1993) at the same site where yield responses to drought were resented using potential SWD.

RESULTS

During the first year after field planting (February 1996 to January 1997), the overall survival rate was 89%. The mean field survival rates of scion clones S15/10 and K35 were 88% (ranging between rootstocks 83 - 90%) and 91% (range 84 - 98%) respectively. The corresponding survival rates from the ungrafted plants of clones S15/10 and K35 were 86 and 91%. For the rootstock treatments the field survival rates were in the range 84 - 94%, with the highest from rootstock SFS150. The highest survival rate (98%) was obtained from scion clone K35 grafted onto rootstock SFS150.

On the basis of survival rates obtained in the first year after field planting, the field performance of the grafted plants was the same as that of the ungrafted plants. The performance of the plants of the grafted and ungrafted scion clone S15/10 however, tended to be lower than those of scion clone K35.

Dry matter content of harvested shoots

During the period from June 1997 to May 2001 (four full seasons of harvesting), none of the rootstocks had any effect on the dry matter content of the harvested shoots of the scions. The season of the year (described as cool dry, warm dry and warm wet) (see Chapter 3) and drought however, had significant ($P \leq 0.001$) effect on the dry matter content of the harvested shoots. Similarly, scion affected the dry matter content, but the effects were not consistent during the four years of harvesting.

Table 6: Effects of the season of the year on the dry matter content of the harvested shoots of the grafted and ungrafted plants of clones S15/10 and K35.

Season	Cool dry (June to August)	Dry matter content (%) Warm dry (September to November)	Warm wet (December to May)	s.e.d (df = 47)
1997/98	24.9	23.4	22.8	0.337
1998/99	25.3	22.7	22.4	0.354
1999/00	25.4	22.9	22.1	0.235
2000/01	25.4	23.1	22.6	0.490
Mean	**25.3**	**22.9**	**22.5**	

The highest (25.3%) and lowest (22.5%) mean dry matter content of harvested shoots were obtained during the cool dry (June to August) and warm wet (December to May) seasons respectively (Table 6).

Yield

During the first five months of harvest (December 1996 to May 1997), all rootstocks improved the yield of scion clone S15/10. By contrast, none improved the yield of scion clone K35. The mean yields of dried tea from graft combinations with S15/10 as a scion were in the range 380 - 530 kg ha^{-1}, with the highest yield when grafted onto rootstock PC81. The yield of the ungrafted scion S15/10 was 250 kg ha^{-1}. The corresponding yields from scion K35 were 300 - 410 kg ha^{-1} from the grafted and 310 kg ha^{-1} from the ungrafted plants. Grafting scion clone S15/10 onto rootstock K35 increased the yield of clone S15/10 by 150 kg ha^{-1}. By comparison, the yield of the opposing grafting (i.e. K35 onto S15/10) was similar to that of the ungrafted plants of clone K35.

In the first full year of yield recording (1 June 1997 to 31 May 1998), during which time the experiment was uniformly irrigated, there were no significant effects of rootstock on the annual yields of the clones used as scions. The mean yields of dried tea of scion clone S15/10 grafted onto the three rootstocks (PC81, 6/8 and SFS150) were in the range 3,040 - 3,540 kg ha^{-1}. By comparison the ungrafted plants of scion clone S15/10 yielded 2,480 kg ha^{-1}. The corresponding yields from scion K35 were 2,810 - 3,080 kg ha^{-1} from composite plants and 2,780 kg ha^{-1} from the ungrafted control (Figure 17). Similarly, when the two scions were grafted onto each other the yields were the same as those from their respective ungrafted plants. Clone S15/10 grafted onto rootstock K35 yielded 11% more than K35 grafted onto rootstock S15/10.

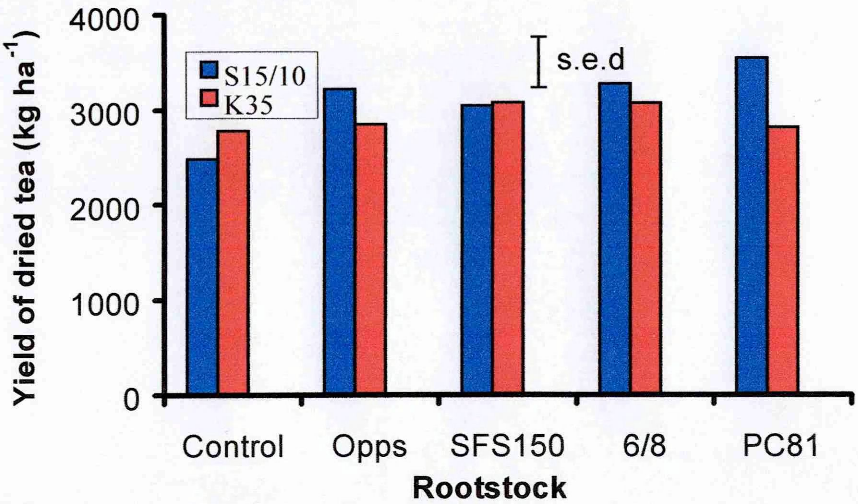


Figure 17: Effects of rootstock clone on the annual yield (1 June 1997 to 31 May 1998) of dried tea from scion clones S15/10 and K35. 'Opps' refers to the rootstock/scion combinations S15/10 on K35 and vice versa. "Control" refers to the ungrafted scions. S.e.d. n = 12.

In the second (1998/99), third (1999/00) and fourth (2000/01) full seasons of harvesting, during which irrigation treatments were imposed, only irrigation and scion, and their interaction had significant effects on the mean annual yields of dried tea of the scions. During 1998/99, as expected, the highest yield (5,200 kg ha^{-1}) was recorded from the fully irrigated plots, compared to 3,240 kg ha^{-1} from the unirrigated*. For scion clone S15/10, the mean yields from the fully irrigated and the unirrigated plots were 5,800 and 3,730 kg ha^{-1} respectively. The corresponding yields from scion clone K35, which were all less than those of scion S15/10 were 4,600 and 3,120 kg ha^{-1} (Figure 18).

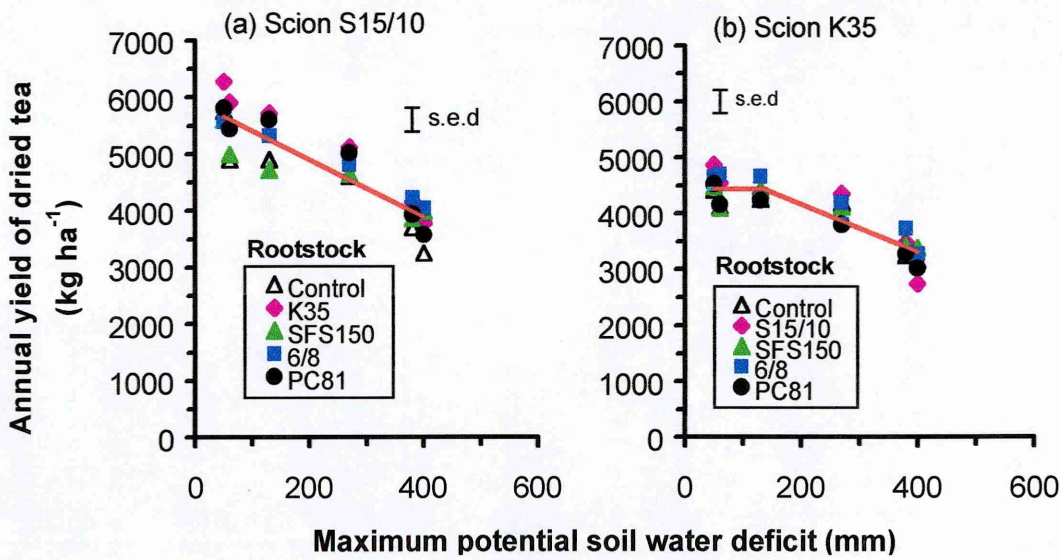


Figure 18: Effects of maximum potential soil water deficit on the mean annual yield of dried tea (1 June 1998 to 31 May 1999) of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scion clones. The equation of the line in Figure (a) is $y = -5.0$ *(s.e. 0.64)*$x + 5909$ *(s.e. 165.97);* $R^2 = 0.94$ *and that of the sloping line in Figure (b) is* $y = -4.2$*(s.e. 0.148)*$x + 5008$ *(s.e. 46.62);* $R^2 = 0.99$.

For scion clone S15/10, the mean yields across irrigation treatments were in the range 4,630 - 5,160 kg ha^{-1}, with the lowest and highest when grafted onto rootstocks SFS150 and K35 respectively. By comparison the ungrafted clone S15/10 yielded 4,520 kg ha^{-1}. For scion K35 the corresponding range was 3,840 - 4,210 kg ha^{-1}, with the lowest and highest when grafted onto rootstocks PC81 and 6/8. The ungrafted K35 had a mean yield of 3,910 kg ha^{-1}. The mean yield from scion clone S15/10 (across all rootstock treatments) decreased linearly with maximum potential soil water deficit at a rate of 5.0 kg (ha mm)$^{-1}$ (Figure 18 a). For scion clone K35 there was a two-step linear

* *Although referred to unirrigated, the plants were irrigated at the beginning and sometimes before the end of the dry season to avoid plant death due to water stress.*

relationship (Figure 18 b). The yield remained constant at about 4,440 kg ha^{-1} at SWDs between 0 and 130 mm, then decreased linearly at a rate of 4.2 kg (ha mm)$^{-1}$.

Grafting scion clone S15/10 onto rootstock K35 increased the yield of dried tea from 3,250 to 3,790 kg ha^{-1}, and from 5,760 to 6,280 kg ha^{-1} in the driest and fully irrigated plots respectively. The opposing grafting (K35 onto rootstock S15/10) however, increased the yield (from 4,430 to 4,880 kg ha^{-1}) only in the fully irrigated plots, whereas it was decreased (from 3,170 to 2,750 kg ha^{-1}) in the unirrigated plots.

In 1999/00 (third season) the mean annual yield of dried tea across all treatments of scion clone S15/10 was 5,300 kg ha^{-1}, compared with 4,640 kg ha^{-1} from K35. For scion clone S15/10, the mean yield across all rootstocks was 6,560 kg ha^{-1} from the fully irrigated plots, compared with 3,750 kg ha^{-1} from the unirrigated plots. The corresponding yields from scion clone K35 were 5,410 and 3,320 kg ha^{-1} (Figure 19).

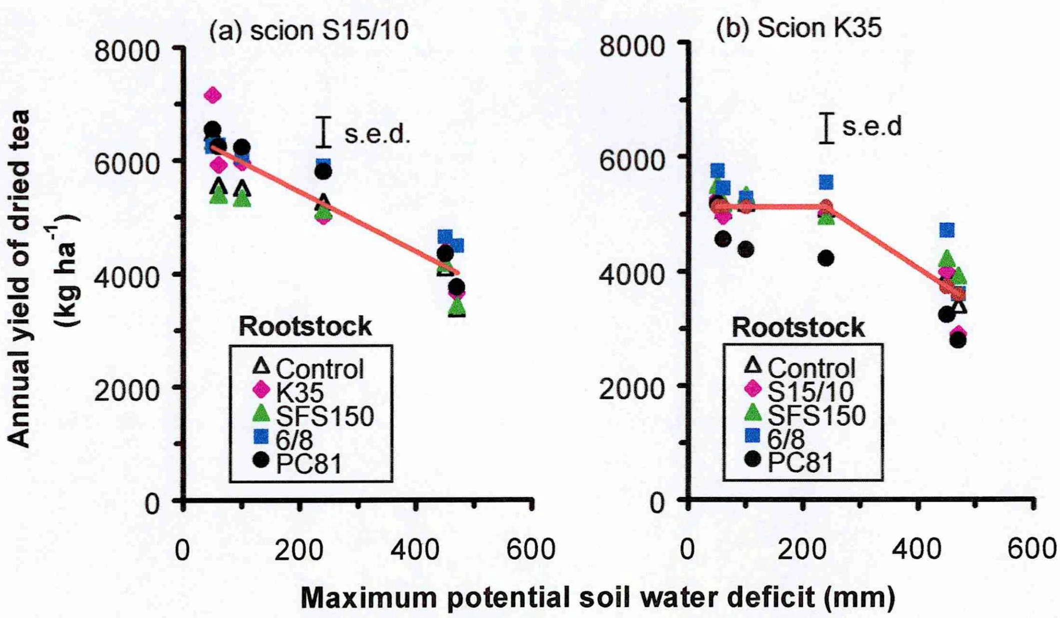


Figure 19: Effects of maximum potential soil water deficit on the mean annual (1 June 1999 to 31 May 2000) yield of dried tea of (a) scion S15/10 (b) scion K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scions. The equation of the line in Figure 3(a) is $y = -5.3(s.e.\ 0.706)x + 6507\ (s.e.\ 203.28)$; $R^2 = 0.93$ and that of the sloping line in Figure (b) is $y = -6.7(s.e.\ 0.009)x + 6729\ (s.e.\ 3.73)$; $R^2 = 0.99$.

As in the previous season, the yield responses to drought of the two scions were different, being linear for scion S15/10 and two-step linear relationship for K35. For scion clone K35, unlike the previous season when the yields remained constant (at 4,440 kg ha^{-1}) at SWDs between 0 and 130 mm, the yields remained constant (at about 5,130 kg ha^{-1}) up to 240 mm of SWD; then decreased linearly at a rate of 6.7 kg (ha mm)$^{-1}$ (Figure 19 b). Similarly, the rate of yield decrease above 240 mm of SWD was higher than that of 1998/99 season (4.2 kg (ha mm)$^{-1}$).

During the fourth full year of harvesting (2000/01), as in the previous years, the rootstocks did not improve the annual yields of the scions. Across all treatments, the mean yield of dried tea of scion clone S15/10 was 5,730 kg ha^{-1}, which was higher than that of scion clone K35 (5,180 kg ha^{-1}). For scion clone S15/10, the mean yield across rootstock treatments was 6,760 kg ha^{-1} from the fully irrigated plots, compared with 4,020 kg ha^{-1} from the unirrigated plots. The corresponding yields from scion clone K35 were 5,870 and 3,670 kg ha^{-1} (Figure 20).

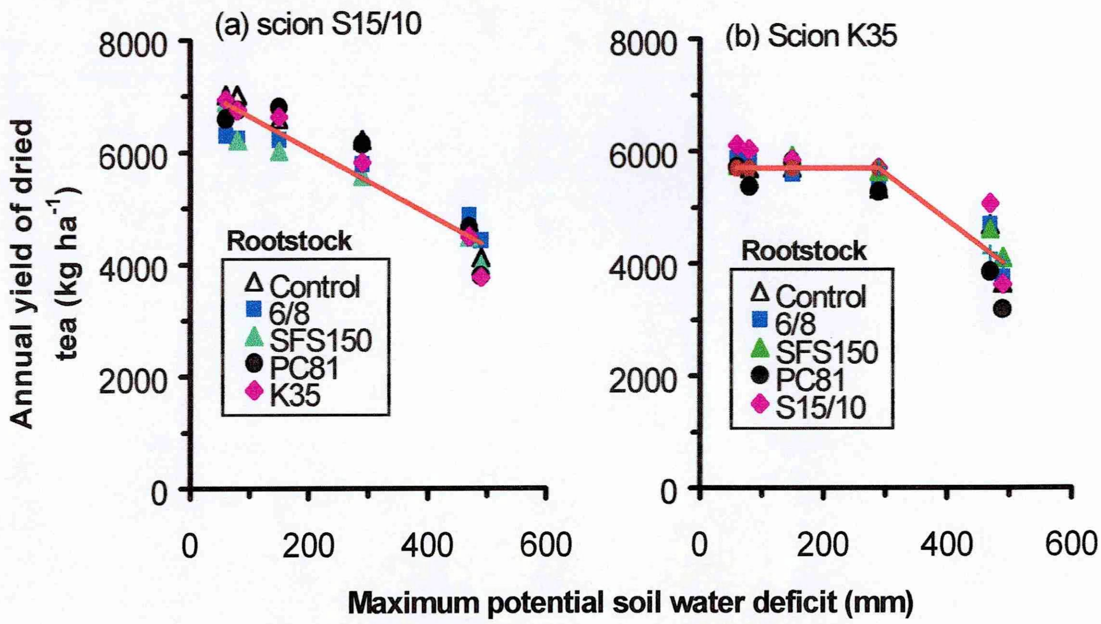


Figure 20: Effects of maximum potential soil water deficit on the mean annual (1 June 2000 to 31 May 2001) yield of dried tea of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scions. The equation of the line in Figure (a) is $y = -5.8(s.e.\ 0.682)x + 7220\ (s.e.\ 211.63);\ R^2 = 0.95$ *and that of the sloping line in Figure (b) is* $y = -8.4(s.e.\ 0.092)x + 8138\ (s.e.\ 39.04);\ R^2 = 0.99.$

In the well watered plots, the ungrafted plants of clone S15/10 yielded 7,020 kg ha^{-1} compared with 6,310 – 6,950 kg ha^{-1} from the grafted plants. Likewise, in the driest treatments with the exception of rootstock 6/8 which yielded higher (although not significantly), the mean yields (3,780 – 3,990 kg ha^{-1}) of tea from all other graft combinations were lower than that of the ungrafted plants of scion clone S15/10 (4,120 kg ha^{-1}). For K35 graft combinations, the yields were 5,720 – 6,120 kg ha^{-1} and 3,190 – 4,110 kg ha^{-1} from the irrigated and unirrigated plots respectively. The corresponding yields from the ungrafted plants were 5,890 and 3,650 kg ha^{-1}.

Yield trend

In the well watered treatments, the mean annual yields (across rootstock treatments) of scion clone S15/10 increased from 3,110 kg ha^{-1} in 1997/98 to 6,760 kg ha^{-1} in 2000/01 season. The corresponding annual yield from scion clone K35 increased from 2,920 kg ha^{-1} to 5,870 kg ha^{-1} (Table 7). For scion clone K35, the critical deficit above which yields declined increased from 130 in 1998/99 (when differential irrigation treatments were applied for the first time) to 290 mm in 2000/01 season (about 5 years after field planting). By contrast, the critical deficit for scion clone S15/10 remained constant at 50 - 60 mm during the same period.

Table 7: Summary of maximum yields (across rootstock treatments) from the fully irrigated plots, critical deficit and yield responses to drought over years of scion clones S15/10 and K35 grafted onto rootstocks SFS150, PC81 and 6/8.

	Scion					
	S15/10			K35		
Year	Maximum yield (kg ha^{-1})	Critical deficit (mm)	Slope kg (ha mm)$^{-1}$	Maximum yield (kg ha^{-1})	Critical deficit (mm)	Slope kg (ha mm)$^{-1}$
1997/98	3,110	-	-	2,920	-	-
1998/99	5,800	50	5.0	4,600	130	4.2
1999/00	6,560	50	5.3	5,410	240	6.7
2000/01	6,760	60	5.8	5,870	290	8.4
Mean	**5,560**	**50**	**5.4**	**4,700**	**220**	**6.4**

N.B. The experiment was uniformly irrigated in the first 30 months after planting to ensure successful crop establishment.

In the unirrigated treatments, the yields trend with year after planting showed that with exception of rootstock SFS150 in year 4, the grafted plants of scion clone S15/10 consistently yielded higher than the ungrafted plants between year one and year 4 (Figure 21 a). In year 5 however, only rootstock 6/8 continued to out-yield the ungrafted plants of clone S15/10. For scion clone K35 only when was grafted onto rootstock SFS150 consistently yielded higher than the ungrafted plants (Figure 21 b).

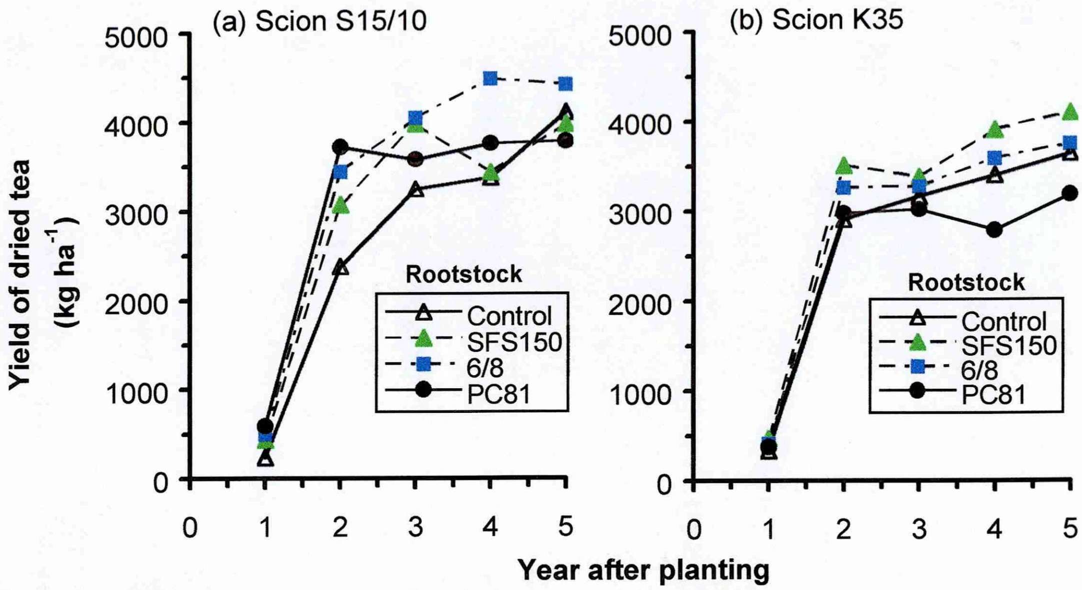


Figure 21: Yields of dried tea from the unirrigated plots of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, 6/8 and PC81, with year after planting (February 1996). Control refers to the ungrafted scion clones. The yields in year one were only for the first five months. The plots were uniformly irrigated in year 1 and 2.

Relative yield increase due to rootstocks

For both scions, the mean annual yields from the fully irrigated plots were higher than those from the unirrigated, with scion clone S15/10 out-yielding K35. By contrast, the relative yield increases** due to rootstocks from the unirrigated plots were higher than from the well-watered plots. The yield increases however, varied with scion clone. For scion clone S15/10 the mean annual yield increase (means of three seasons) was 310 kg ha^{-1} (9%) from the unirrigated plot. By contrast, the corresponding mean annual yield increase from scion clone K35 was less than 1%. In the well watered treatments, the overall yield increases were less than 3% for both scions (Table 8).

*** The relative yield increase is defined as the difference between the mean annual yield of dried tea of the grafted plants and their respective ungrafted scions grown under the same water regime.*

Table 8: Effects of rootstock on the mean annual yield of dried tea (for three seasons, 1 June 1998 to 31 May 2001) and annual yield difference of irrigated and unirrigated scion clones (a) S15/10 and (b) K35 grafted onto rootstocks 6/8, SFS150 and PC81. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scion clones.

(a) S15/10

Rootstock	Irrigated Annual yield (kg ha^{-1})	Yield difference (kg ha^{-1})	Yield difference (%)	Unirrigated Annual yield (kg ha^{-1})	Yield difference (kg ha^{-1})	Yield difference (%)
Control	6,420	-	-	3,580	-	-
K35	6,790	370	6	3,740	160	4
6/8	6,040	-380	-6	4,320	740	21
SFS150	6,280	-140	-2	3,800	220	6
PC81	6,320	-100	-2	3,710	130	4
Mean	**6,370**	**-60**	**-1**	**3,830**	**310**	**9**
s.e.d. between irrigation treatments (annual means) = 82 (df = 4).						

(b) K35

Rootstock	Irrigated Annual yield (kg ha^{-1})	Yield difference(kg ha^{-1})	Yield difference (%)	Unirrigated Annual yield (kg ha^{-1})	Yield difference (kg ha^{-1})	Yield difference (%)
Control	5,220	-	-	3,410	-	-
S15/10	5,420	220	4	3,100	-310	-9
6/8	5,430	210	4	3,550	140	4
SFS150	5,250	30	1	3,800	390	11
PC81	5,140	-80	-2	3,000	-410	-12
Mean	**5,290**	**90**	**2**	**3,370**	**-50**	**-1**
s.e.d. between irrigation treatments (annual means) = 82 (df = 4).						

Yield responses to water

Although in the previous sections, the yield responses were expressed as yield per mm of potential soil water deficit, it is also useful to express the yield responses to actual amount of water applied. This enables an estimation of yield benefit per mm of water applied if the cost of application is known. Similarly, based on the yield response to actual amount of water applied, it is possible to identify tea cultivars or rootstock/scion combinations, which can maximize return under irrigation.

Across all treatments, the overall mean yield response to water (mean of three seasons) of scion clone S15/10 was 5.1 kg (ha mm)$^{-1}$, compared with 3.9 kg (ha mm)$^{-1}$ from scion clone K35. For scion clone S15/10, the yield responses to water of the grafted plants were in the range 3.4 - 6.1 kg (ha mm)$^{-1}$; the lowest and highest when it was grafted onto rootstocks 6/8 and K35 respectively. For the ungrafted plants of scion clone S15/10 the response was 5.7 kg (ha mm)$^{-1}$. The corresponding values for K35 graft combinations were in the range 2.9 - 4.7 kg (ha mm)$^{-1}$; the lowest and highest when it was grafted onto rootstocks SFS150 and S15/10. The yield response to water of the ungrafted plants of scion clone K35 was 3.6 kg (ha mm)$^{-1}$.

DISCUSSION

Dry matter content of harvested shoots

Variations in the mean air temperature between the seasons and the potential soil water deficit are the main factors that caused the observed seasonal differences in dry matter content of the harvested shoots (Burgess, 1992c; Cloughley, 1981; Ng'etich, 1995). The higher dry matter content obtained during the cool months (June to August) was due to slow shoot development and extension rates caused by low temperatures, resulting in older (due to longer harvesting intervals) and therefore more fibrous shoots.

Although the dry matter content of harvested shoots differed significantly for the scions, the effects were not consistent and were therefore excluded in the derivation of the conversion factors used in converting fresh weight of harvested shoots into dry weight. Similarly, the effects of soil water deficit on the dry matter content was excluded because the net effect of a dry soil on dry matter content tends to be small as it reduces yield directly (Burgess, 1992c). Since the rootstocks had no effect, then only the season was used to derive the conversion factors (Table 6).

Burgess (1992b) and Ng'etich *et al.* (1995) reported clonal differences in dry matter content of harvested shoots. It was therefore anticipated that the rootstocks might influence the dry matter content of the harvested shoots of the scions, probably by influencing shoot growth rates. In this study however, the rootstocks had no effect on the dry matter content, suggesting that shoot dry matter is controlled by temperature effects on scion shoot growth rates.

Yield

During the first five months of harvest (tipping) rootstocks significantly increased the yields of scion clone S15/10. Measurements of ground cover showed that by the end of June 1997, plants of ungrafted clone S15/10 had reached a mean ground cover of 40%, compared to 46 - 52% from its graft combinations. Similar results were reported by Ng'etich (1995) where clone S15/10 had low ground cover in the first two to three years after field planting. The early higher yields obtained from the grafted than the ungrafted plants of scion clone S15/10 therefore, could be due to the inherent difficulties that clone S15/10 has in establishing when planted on its own roots.

Since a composite plant is made up of two genetically different cultivars, the plant growth at the initial stages may be affected by the way the scion responds to the growth of the rootstock and *vice versa,* a process referred to as early imbalance between rootstock and scion (Tubbs, 1973a). This imbalance diminishes as the equilibrium between them is attained. The yield increases obtained for the grafted plants of clone S15/10 in the first five month of harvesting might also be caused by the early imbalance between the rootstocks and the scions of this clone. In fruit trees similar effects were reported (Tubbs, 1973a), where trees up seven years old were still influenced by (although to a diminishing degree) an early imbalance between rootstock and scion. Evaluation of composite tea plants in Malawi revealed that while the yield benefits appear more pronounced as the bushes mature in some rootstock/scion combinations (TRFCA, 1996), in other combinations the yield benefits decreased with year from planting (TRFCA, 1995). All these findings suggest that the evaluation of composite plants should not only consider the yields at the initial stages but also yields for longer periods.

Yield responses to drought

Although there were no significant effects of rootstocks on the mean annual yields of the scions for all of the four years (1 June 1997 to 31 May 2001), some rootstocks appeared to improve the yield and drought tolerance of the scions. The yield responses to drought of the two scions however, were different during the three years when the differential irrigation treatments were applied (Figure 18, Figure 19 & Figure 20). The effect of rootstocks on the yields of the two scions observed in this study, confirm the early findings by other researchers (Corley, 1992; Nyirenda, 1987; Nyirenda and Kayange, 1984; Satyanarayana *et al.*, 1991; Smith and Bayliss, 1994) that the influence of a rootstock on the attributes such as yield and drought tolerance of the scion depends on the scion used.

The yield responses to drought of the grafted plants followed the same pattern as that of the ungrafted plants irrespective of the rootstock used, suggesting that the scions dominated the yield responses to drought. This might be through regulating their transpiration and/or water use efficiency. Since this is the first study in tea where composite tea plants have been systematically evaluated over wider range of water regimes, it is not clearly known what mechanisms are involved. The time and the details required to study these mechanisms as well as the cost involved meant that it was not possible to determine the mechanisms involved in the yield responses to drought of a composite plant.

In apple composite plants, differences in root and stem anatomy were reported to affect the translocation efficiency of water and minerals, or complex molecules such as carbohydrates and plant hormones (Beakbane and Thompson, 1939, cited by Webster, 1995). Likewise, Jones (1992), and Lovisolo and Schubert (1998) suggested that the movement of water in plants is controlled by the conductance of the water pathways (i.e. roots, shoots and stomata) as well as the efficiency of water transport system. When exposed to water stress, plants show modifications in the water flow rate due to adjustments in the water flow pathways (Lovisolo and Schubert, 1998). The scions therefore might have dominated the yield responses to drought by controlling the whole process of water flow along the soil-plant-atmosphere water pathway.

Jones (1992) reported that the effect of soil drying on processes such as shoot growth and photosynthesis may be mediated by signalling (possibly involving abscisic acid (ABA)) from the roots to the shoots. The idea was supported by Lambers *et al.* (1998) and Davies *et al.* (1994) who, speculated that the roots sense the drying soil through ABA. This is because the concentration of ABA in the roots (in contact with the soil) increases when plants are exposed to water stress. Likewise, work in maize and sunflower (Zhang and Davies, 1990) revealed the same findings that ABA plays a major role on chemical signals in the root-to-shoot communication in a drying soil. It is an important component, which modifies the growth and development as a result of a prolonged drought period. Work at the Horticulture Research International, U.K. (HRI, 1997) also supported the involvement of ABA in root-to-shoot communication. The work also proposed other growth substances such as the auxins, cytokinins and gibberellins, which have major roles in determining shoot and root growth and development. The signals induced by these chemicals influence the co-ordination of root and shoot growth and development. These signals play a major role on the plant responses to drought. The observed differences in yield response to drought between the two scion clones therefore might be caused by different root to shoot signals, which affected shoot growth and development differently as the soil water deficit increased.

Critical deficit

The increase in critical deficit (from 130 mm in 1998/99 to 290 mm in 2000/01) above which yields of scion clone K35 decreased, indicates that the resistance to drought of these plants had increased. The critical deficit (290 mm) reached during 2000/01 season (about 5 years after field planting) was similar to that reported by Nixon (1996) (250 - 340 mm) for 4 - 8 year old clonal tea. The effects of both rootstock and ageing account for the increase in drought resistant of the plants of scion clone K35. As the plants age, the rooting depth and root density increase which improves the capacity of the plants to extract water from the soil. Such effect, however, were not observed for scion clone S15/10 in which the critical deficit remained at 50 – 60 mm. As suggested earlier, if root-to-shoot signalling is involved in plants when soil water is limited, then it appears that the plants of the two scions had different capacity of responding to these signals. The plants of scion clone S15/10 responded to the signals and regulated shoot growth and development much earlier than those of scion clone K35.

Relative yield increase due to rootstocks

The observed higher relative yield increases from the grafted plants in the unirrigated plots as compared to the fully irrigated suggest that soil water availability modified the influence of the rootstocks on the yield of the scions. As suggested above several water dependant mechanisms might have been involved which at the moment are not clearly understood. In other crops possible processes were proposed. Webster (1995a) suggested that rootstocks bring about their effects upon the scion by influencing the amounts and/or ratios of promoting and inhibiting hormones circulating between the root system and the aerial tree part; the movement of assimilates between the rootstock and the scion as well as the water uptake and movement in the plant. Olien and Lakso (1986) reported that the growth of apple composite plants is controlled by the balance of cytokinin and auxin between the scion and the rootstock. Similarly, the extra ABA in the xylem, resulting from the effect of soil drying affected the growth and physiology of maize and sunflower plants (Zhang and Davies, 1990). These chemical substances induce chemical signals, which influence the root and shoot growth and development (HRI, 1997).

The ABA concentration rises rapidly in a stressed plant (Davies *et al.*, 1994; De Wit and Penning de Vries, 1983; Jones, 1992; Lambers *et al.*, 1998), which suggests that the plant root-to-shoot signals induced by ABA at different levels of plant water stress will be different. The soil water availability affects the levels of these chemical substances in the plants, which result in different root-to-shoot signals that influence the growth and development of the plants. These processes might have caused the observed differences in the relative annual yield increases between the well watered and the unirrigated treatments.

As presented in Table 8, the mean annual yield increases from the two scions in the unirrigated plots were different. The yields of scion clone S15/10 were improved for most of the rootstocks as compared to scion clone K35. Of all rootstocks, only SFS150 improved the yield of clone K35 in the driest treatments. It is likely that the mechanisms described above caused the observed differences in yield increase between the two scions in the unirrigated plots. If the root-to-shoot signalling controls plant growth, then it appears that the rootstocks have influence (which depends on the scion used) on the levels and therefore the signals, which affect the growth and yield of the scions. For example, termination of extension growth in perennials with formation of dormant buds (Jones, 1992; Zhang and Davies, 1990) is one of the effects of water deficit on vegetative development and is an important strategy employed by plants to limit water loss during a prolonged drought. Probably, the critical deficit above which the rootstock signals the scion to terminate extension growth (form dormant buds) depends on the scion used, suggesting that the plants of scion clone K35 formed dormant buds earlier than those of clone S15/10.

The fact that the relative yield increases obtained from some combinations in the unirrigated plots were higher than from the well-watered treatments suggests that some rootstocks might have improved the drought tolerance of the scions. In the driest plots all rootstocks tested increased the annual yields (130 - 740 kg ha^{-1}) of scion S15/10, with the highest when grafted onto rootstock 6/8. Similarly, in the unirrigated treatments, the annual yield of scion clone K35 increased by 390 kg ha^{-1} when grafted onto rootstock SFS150.

Nixon (1996) compared the drought responses of clones SFS150, 6/8, K35 and S15/10 at about the same age as the plants in this study. The results showed that clone K35 was the most sensitive to drought followed by S15/10, 6/8 and SFS150 in that order. The yield increase obtained from scion clone S15/10 grafted onto rootstock 6/8 in the unirrigated plots was unexpected. Both clones 6/8 and S15/10 are described as drought susceptible (Burgess, 1992b). It is surprising to see that, when clone S15/10 was grafted onto 6/8, the resulting composite plants yielded higher than the ungrafted clone S15/10. Rootstock 6/8 however, did not have the same effects on scion clone K35, which is also described as drought susceptible (Carr, 1995; Ng'etich *et al.*, 1995). By contrast, clone SFS150 is a drought tolerant clone and maintained this characteristic when used as a rootstock for the two scions. All these findings demonstrate that the individual clonal characteristics, which are the common criteria used to select rootstocks and scions may or may not be maintained in the resulting composite plants and therefore may not on their own be reliable selection criteria. In addition to the individual clonal characteristics, criteria are required to match the scions to the appropriate rootstocks to improve the expected attributes.

In Kericho, clone S15/10 performed well as a rootstock (Smith and Bayliss, 1994). In this study however, the use of clone S15/10 as rootstock did not improve the yields of scion clone K35 under both fully irrigated and rainfed conditions. This could be due to differences in environmental factors, but also depends on the scion clones used. Both the amount (about 2,150 mm per year, Bore, 1997) and distribution of rainfall at Kericho as well as temperature favour tea growth, compared to Mufindi. Clone S15/10 normally partitions more of its dry matter to leaves than roots (Burgess, 1992b; Kigalu, 1997; Ng'etich, 1995). The poor performance of clone S15/10 as a rootstock particularly as the soil water deficit increases could be due to the inability of this clone to partition its dry matter more to the roots to cope with the moisture stress. In fact the yield increases obtained when clone S15/10 was used as a scion could be due to a combined effects of rootstocks and dry matter partitioning. Clone S15/10 might have continued to partition more dry matter to leaves than roots when used as a scion. If so then dry matter partitioning could be a useful guide for selecting rootstocks and scions. Tea clones that partition more dry matter to leaves are probably good scions, and those which partition more to roots might be good rootstocks.

Measurements of xylem water potential (Chapter 4) during the dry season indicated broadly that the rootstocks improved the drought tolerance of scion clone K35 more than S15/10. Similarly, visual assessment during 2000 dry season clearly showed that the unirrigated plots of scion clone S15/10 were worse affected by water stress, whilst those of scion clone K35 remained green (although not flushing). The rootstocks tested therefore improved two different attributes of the two scions. For scion clone S15/10, most of the rootstocks improved the annual yield, but did not improve the survival/drought tolerance of this clone during the dry season. By comparison, with the exception of rootstock SFS150 which improved both yield and drought tolerance, no other rootstocks tested improved the annual yield of scion clone K35, but improved the drought tolerance (survival) during the dry season (see Chapter 4). This means that although the yield loss during the dry season was compensated in the rainy season for scion clone S15/10, to give a net benefit on an annual basis, it is likely that more bushes of this scion clone will be lost if a prolonged drought period occurs as compared to plants of scion clone K35. These observations suggest that yield and drought tolerance (survival during severe drought) should be considered separately during selection of rootstocks. These attributes are not necessarily combined in all rootstocks.

In the unirrigated plots, the mean annual yield increases (130 - 740 kg ha^{-1}) from some of the rootstock/scion combinations obtained in this study are higher than the current average annual yield (200 kg ha^{-1}; Carr, 1999) from smallholders in Tanzania. This suggests that these combinations appear to have potential for rainfed tea producers in areas prone to drought. However, in the absence of guidelines on yield increase in absolute terms, which can be considered economically viable in a given production system, it is difficult to draw firm conclusions from the yield increases obtained in this study. In studies comparing yield levels, it is necessary to establish an absolute yield increase necessary to pay the increased investment. That is the minimum total yield increase required to pay the extra cost of producing plants by grafting (see Chapter 8).

The lack of significant effect of rootstocks on the yields of the scions observed in this study could be due to the rootstock/scion combinations used. The individual clonal characteristics were used to select the rootstocks and scions. In absence of criteria for matching scions to appropriate rootstocks to produce composite plants of the desirable attributes, the individual clonal characteristics were again used as a guide to match the scions to the rootstocks. For example a drought tolerant clone was used as a rootstock, whilst a drought susceptible was used as a scion, anticipating that the rootstock will improve the drought tolerance of the scion. The results from this study however, suggest that not all drought susceptible scion clones will benefit when grafted onto a drought tolerant rootstock. Depending on the combination, the rootstock and/or the scion may or may not maintain its characteristics in the resulting composite plants.

Evaluation of composite tea plants in Malawi (TRFCA, 1996) where scion clones PC80 and SFS150 were grafted onto rootstocks PC87, MFS87, MFS97, MFS61 and PC81 supported the above view. While all rootstocks consistently improved the yield of scion clone PC80 for fifteen years, the rootstocks did not improve the yield of scion clone SFS150 over the same period.

All these results suggest that apart from the individual clonal characteristics additional criteria are needed to match the scions onto the appropriate rootstocks to improve the expected attributes.

The lack of significant rootstock effects on the yield of the scion might also be caused by the fewer number of replicates in the experiment. The poor success rate obtained in the nursery meant that the plants were enough for two replicates.

CONCLUSIONS

The rootstocks had no significant effect on the dry matter content of the harvested shoots of the scions. The dry matter content however, varies with season of the year. The highest (25.3%) and lowest (22.5%) dry matter content was obtained during the cool dry (June to August) and warm wet (December to May) seasons respectively.

During the first four full seasons of harvesting, although not significantly different, some rootstocks improved the yield and drought tolerance of the clones used as scions. For example, in the unirrigated plots, a mean (of three seasons) annual yield increase (across rootstock treatments) of 310 kg ha^{-1} (9%) was recorded from scion clone S15/10. By contrast, in the well-watered treatments, the rootstocks did not improve the yield of clone S15/10. For scion clone K35 however, the overall annual yield increase whether irrigated or unirrigated was less than 3%.

On the basis of annual yields in the unirrigated plots, in which mean yield increases of 130 - 740 kg ha^{-1} were obtained, some rootstock/scion combinations tested appear to have potential for rainfed tea growers in areas prone to drought. While clone S15/10 seems to be a good scion when grafted onto most of the rootstocks, with the best combinations when grafted onto rootstock 6/8 and SFS150, for scion clone K35 only grafting onto rootstock SFS150 forms a suitable combination under rainfed conditions.

Although the individual clonal characteristics are commonly used to select rootstocks and scions, these characteristics on their own are not reliable criteria of selecting and rootstocks/scion combinations. Additional criteria are required to match the scions to the appropriate rootstocks to produce composite plants that will improve the expected attributes. Since both internal and external factors seem to play a major role in the growth of a composite plant, the criteria for matching rootstock/scion combinations should perhaps include those related to internal (e.g. the genetic make up/closeness of a scion and a rootstock) and external factors (e.g. climate, soils and altitude).

CHAPTER 6

COMPOSITION OF HARVESTED SHOOTS

INTRODUCTION

The potential of some rootstocks to increase the yields of the scions has been recognised in many tea growing regions. In East and Central Africa (Corley, 1992; Nyirenda, 1990; Nyirenda, 1995; Smith and Bayliss, 1994; TRFCA, 1995), South India (UPASI, 1985) and Sri Lanka (Pallemulla *et al.*, 1992) some rootstocks increased the yields of the clones used as scions. As the profit of the tea industry depends not only on the quantity, but also on the quality and the value of the processed tea, the yield increases obtained from composite plants may not be of much benefit if the quality of made tea is affected. Previous work (Bore *et al.*, 1995; Kayange *et al.*, 1981; Pool and Nyirenda, 1981) however, revealed that rootstocks increased the yields of the scions without significant effect on the quality of made tea. Analytical methods to determine the levels of some chemical compounds such as theaflavins (TF), thearubigins (TR) and caffeine as well as sensory evaluation (i.e. colour, brightness, briskness and thickness) are normally used to assess the quality of the processed tea.

The quality of the processed tea depends on the genetic make up of the tea cultivars, and the environmental growing conditions as well as the cultural practices (Owuor, 1995). Application of high rates of nitrogen fertilizer (Hilton and Ellis, 1972; Owour, 1992; Owuor *et al.*, 1995) and harvesting policy (Owuor, 1995; Stephens and Carr, 1994; Willson, 1992) are among the cultural practices which affect the quality of made tea. The harvesting policy basically determines the composition (i.e. shoots of different sizes/stages and the proportions of coarse and broken leaf) of the harvested green leaf. The quality of the green leaf harvested and thereafter the quality of the processed tea depends on the proportions of these categories. This is because the levels of chemical compounds which determines tea quality (see above) differ with shoot size/stage (Owuor, 1995). These levels are known to be high in tender shoots (Kilgour and Brighton, 1999; Obanda and Owour, 1995). Generally, too many large shoots (> 3 leaves and a bud) are undesirable since the manufactured tea will normally be of a lower quality (Jose, 1998; Stephens and Carr, 1994). Similarly, coarse leaf greater than 10% of the total weight of the harvested green leaf has detrimental effects on the quality of made tea (Burgess, 1992a; Jose, 1998).

The composition of harvested shoots namely: the number of shoots per kilogramme of green leaf, the proportions of shoots of different sizes/stages as well as the proportions of coarse and broken leaf have been used successfully to assess the green leaf quality. These are the common criteria used by factory managers to control the green leaf quality at the factory gate.

The composition of harvested shoots depends on the rates of shoot extension and development, which both influenced by several environmental factors. Obago *et al.,* (1988) reported that temperature strongly affects the development and expansion of tea shoots, and thereby the time taken to grow to a size suitable for harvesting. Clonal differences in base temperatures and rates of shoot extension and development seem to suggest differences between clones in the composition of shoots harvested at the same harvesting policy.

In this chapter, the effects of rootstock on the number of shoots per kilogramme of green leaf and the proportions of coarse and broken leaf, as well as the proportions of shoots of different size categories are determined. Apart from the genetic make up of the tea cultivars, these categories play a major role in the quality and therefore the value of the manufactured tea.

METHODOLOGY

As mentioned earlier, the proportions of shoot size categories (e.g. one leaf, two leaves and three leaves and a bud), and coarse and broken leaf in the harvested green leaf determine the quality and value of the final product (see above). To determine these proportions therefore, forty samples (5 rootstocks x 2 scions x 2 irrigation x 2 replicates) each 150 - 200 g from the fully irrigated and the unirrigated plots were collected at each harvest. The samples were divided into coarse broken leaf, soft broken leaf, dormant and growing shoots. A leaf was classified as coarse if it broke, parallel to the mid-rib, when folded on one side (Nixon and Burgess, 1996). To determine the shoot sizes/stages, the growing shoots were further sub-divided into shoots with one, two, three, four or five expanded leaves. The weight and number of shoots in each category were determined. The mean shoot fresh weight at each harvest was calculated as the total weight of harvested shoots divided by the total number of whole shoots. The number of shoots per kilogramme of green leaf was calculated as total number of shoots divided by the total shoot weight (i.e. the inverse of shoot fresh weight). The data were also used to determine the proportions of the total fresh weight that were composed of broken and coarse leaf. Data collected at each harvest for the whole of the 1999/00 crop season were analysed. The harvesting regime was standard and therefore the results were independent of the harvesting method.

RESULTS

Number of harvested shoots per kilogramme

There were no distinct rootstock and irrigation effects on the number of harvested shoots per kilogramme of green leaf. The scion treatments however, affected the number of shoots kg^{-1}. Similarly, the rootstock x scion, scion x irrigation as well as rootstock x scion x irrigation interactions had significant effects on the number of harvested shoots kg^{-1}. The number of shoots (1,220 shoots kg^{-1}) from scion S15/10 was less than from scion K35 (1,300 shoots kg^{-1}).

Table 9: Effects of rootstock on the number of harvested shoots per kilogramme of green leaf from the irrigated and unirrigated plots of scion clones S15/10 and K35 grafted onto rootstocks SFS150, 6/8 and PC81 during 1999/00. "Opp" refers to the graft combination S15/10 onto K35 and vice versa. "Control" refers to the ungrafted scion clones.

Number of shoots per kilogramme of green leaf **Scions**							
	S15/10			K35			**Grand**
Rootstocks	Irrigated	Unirrigated	**Mean**	Irrigated	Unirrigated	**Mean**	**Mean**
Control	1,220	1,160	**1,190**	1,240	1,270	**1,260**	**1,230**
Opp'	1,170	1,190	**1,180**	1,360	1,290	**1,330**	**1,260**
SFS150	1,290	1,240	**1,270**	1,230	1,210	**1,220**	**1,250**
6/8	1,220	1,230	**1,230**	1,270	1,350	**1,310**	**1,270**
PC81	1,270	1,200	**1,240**	1,310	1,500	**1,410**	**1,330**
Mean	**1,230**	**1,200**	**1,220**	**1,280**	**1,320**	**1,300**	**1,260**
s.e.d. between scion treatments = 19.09 (df = 9); rootstock x scion = 42.70 (df = 9); scion x irrigation = 16.21 (df = 7); rootstock x scion x irrigation = 52.29 (df = 7); CV = 3.6%.							

For scion clone S15/10, the number of harvested shoots kg^{-1} from the fully irrigated plots was 1,230 shoots kg^{-1}, which was the same as that of the unirrigated plots. By comparison, the number of harvested shoots (1,320 shoots kg^{-1}) from the unirrigated plots was higher than that from the fully irrigated treatments (1,280 shoots kg^{-1}) for scion clone K35 (Table 9). For both scion clones, with the exception of rootstock PC81, which increased the number of shoots (kg^{-1}) of clone K35, the number of shoots per kilogramme of green leaf from all other rootstock/scion combinations were the same as those of the ungrafted plants.

Proportion of broken leaf

The proportions of the total fresh weight harvested that were composed of broken leaf from the two scion clones were the same. Similarly, neither rootstock nor irrigation treatments had significant effect on the proportion of broken leaf of the scion. The scion x irrigation as well as rootstock x scion x irrigation interactions however, had significant effects on the proportions of broken leaf. Across rootstock and irrigation treatments, the mean proportions of broken leaf from scion clones S15/10 and K35 were 36.9 and 35.9% respectively. For the rootstock treatments, the proportions of broken leaf were in the range 35.6 – 37.5%, which were the same as those from the ungrafted plants (Table 10).

Table 10: Effects of rootstock on the proportion of broken leaf harvested from the irrigated and unirrigated plots of scion clones S15/10 and K35 grafted onto rootstocks SFS150, 6/8 and PC81 during 1999/00. "Opp" refers to the graft combination S15/10 onto K35 and vice versa. "Control" to the ungrafted scion clones.

Proportion of broken leaf harvested (%) **Scions**							
	S15/10			K35			**Grand**
Rootstocks	Irrigated	Unirrigated	**Mean**	Irrigated	Unirrigated	**Mean**	**Mean**
Control	37.6	33.8	**35.7**	33.8	38.3	**36.1**	**35.9**
Opp'	40.7	36.5	**38.6**	36.5	36.0	**36.3**	**37.5**
SFS150	35.1	36.3	**35.7**	36.3	34.7	**35.5**	**35.6**
6/8	37.5	35.6	**36.6**	35.6	33.6	**34.6**	**35.6**
PC81	37.9	37.5	**37.7**	37.5	36.9	**37.2**	**37.5**
Mean	**37.8**	**35.9**	**36.9**	**35.9**	**35.9**	**35.9**	**36.4**
s.e.d. between scion x irrigation = 0.65 (df = 7); rootstock x scion x irrigation = 2.366 (df = 7); CV = 2.5%.							

For scion clone S15/10 the proportion of broken leaf from the fully irrigated plots (37.8%) was higher than from the unirrigated treatments (35.9%). By contrast, the proportions of broken leaf (35.9%) from the two water regimes for scion clone K35 were the same (Table 10).

Proportion of coarse leaf

None of the treatments had any effect on the proportions of the total leaf fresh weight harvested that were composed of coarse leaf. The overall proportion of coarse leaf was 2.0%. Across rootstock and irrigation treatments, the proportions of coarse leaf from the grafted plants of scion clones S15/10 and K35 were 2.0 and 1.8% respectively. These proportions were the same as those from the ungrafted plants.

Shoot development stage

The rootstocks had no influence on the proportion of harvested shoots in any size category. The scion however, had a significant effect on the size of harvested shoots. Greater proportion of the harvested shoots contained shoots with two leaves and a bud for all scions. Of the harvested shoots from the plants of scion clone S15/10 about 33% contained two leaves and a bud, 19% one leaf and a bud and 21% three leaves and a bud. The corresponding proportions from scion clone K35 were 24, 16 and 18% respectively. These proportions were all less than their respective categories from scion clone S15/10 (Figure 22). By contrast, the proportion of dormant shoots from scion clone K35 (41%) was higher than that of scion clone S15/10 (25%). Less than 1% of the harvested shoots had more than three leaves and a bud. For all categories, the proportions of harvested shoots from the grafted plants were the same as that of their respective ungrafted plants.

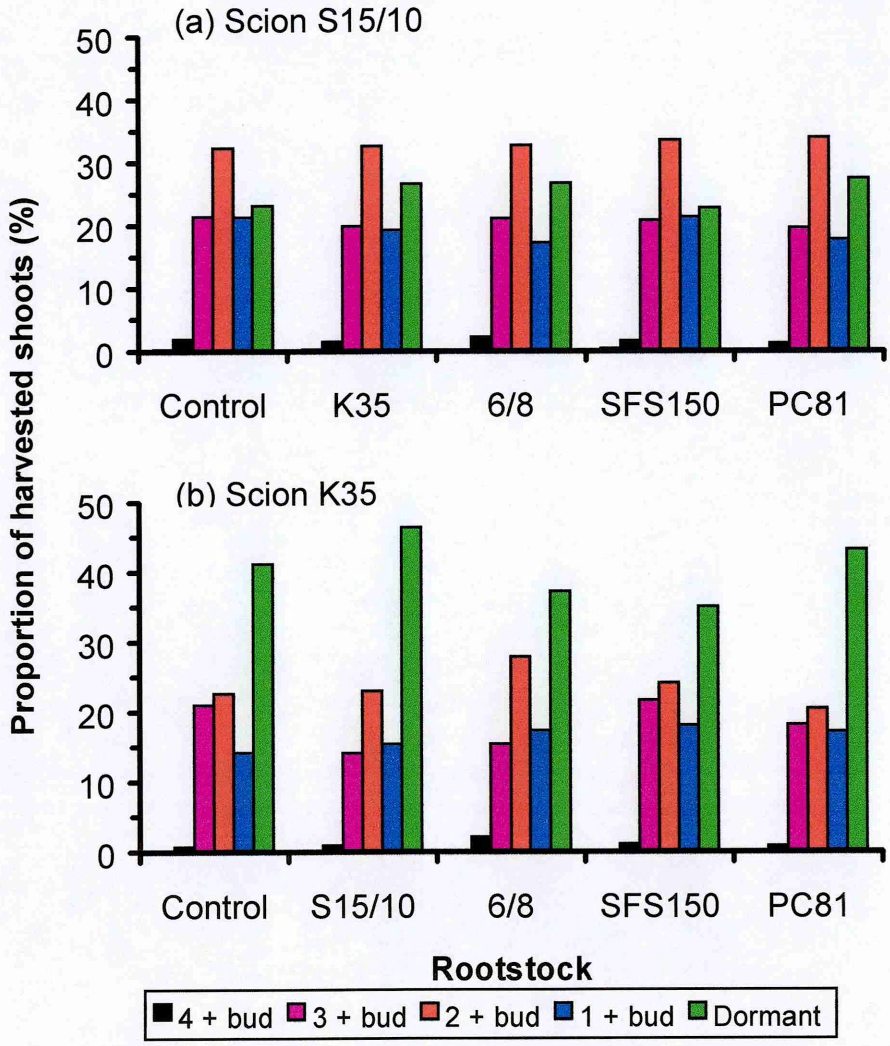


Figure 22: The effects of rootstock on the proportion of harvested shoots of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, 6/8 and PC81. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scions.

DISCUSSION

Number of shoots per kilogramme

The higher number of harvested shoots per kilogramme of green leaf from some rootstock/scion combinations was caused by reduction in shoot fresh weight. For example, the mean numbers of shoots kg^{-1} from scion clone S15/10 and K35 were 1,220 and 1,300 shoots kg^{-1} respectively. The mean shoot fresh weight of scion clone S15/10 (0.82 g) was higher than that of scion clone K35 (0.77 g). Similarly, in the unirrigated plots the number of shoots kg^{-1} from the ungrafted plants of scion clone K35 was only 1,270 compared to 1,500 shoot kg^{-1}, when clone K35 was grafted onto rootstock PC81.

The mean shoot fresh weight of the ungrafted plants was 0.79 g, which was higher than when grafted onto rootstock PC81 (0.66 g). This indicates that rootstock PC81 reduced the mean shoot fresh weight of scion clone K35.

Acceptable green leaf at the factory gate in Southern Tanzania should have at least 1,000 shoots per kilogramme of green leaf for mixed seedling tea (Nixon and Burgess, 1996) and 1,200 shoots (kg^{-1}) for clonal tea (Salim, 2000, personal communication). Across scion and irrigation treatments, the number of shoots per kilogramme of green leaf (1,230 – 1,330 shoots kg^{-1}) obtained was within the acceptable factory standard for clonal tea. In terms of the number of shoots kg^{-1} therefore, the rootstocks had no effect on the quality of the green leaf harvested from all scions.

Proportion of broken leaf

The higher proportion of broken leaf obtained in the irrigated than in the unirrigated plots of scion clone S15/10 could be due to differences in the tenderness of the leaves. Since soil moisture is not a limiting factor in the fully irrigated plots, shoots grow faster with soft leaves in contrast to the unirrigated plots in which shoots tend to be fibrous with hard leaves.

The mean proportions of broken leaf (34 – 40%) obtained were higher than the target figure (20%) suggested by Clowes (1986) for hand harvested tea, but were the same as that previously reported at the same site (Burgess, 1992a; Burgess, 1994b; Nixon and Burgess, 1996). The figure proposed by Clowes (1986) appears to be too low and probably impractical particularly under estate conditions. This is because the leaves of the targeted shoots ($\leq$ 3 leaves and a bud) are tender and therefore break easily. For example over 95% of the broken leaf in this study were soft leaves.

On the other hand, there is no evidence that the soft broken leaves have a detrimental effect on the quality of processed tea. The only disadvantage is that these leaves are prone to uncontrolled fermentation if not delivered to the factory on time.

Proportion of coarse leaf

The overall proportion of coarse leaf of 2% (range 1.6 – 2.5%) was lower than the figure (4%) reported by Nixon and Burgess (1996) from hand harvested clonal tea at the same harvesting interval. This is probably due to differences in the age of the tea and also year after pruning, which might affect the way the shoots grow clear from the old leaves. The tea in this study is only about four years old and has not yet been pruned, whilst that reported by Nixon and Burgess (1996) was 24 years old and was in the last year of the pruning cycle.

The proportion of coarse leaf greater than 10% of the total weight is considered to have a detrimental effect on the quality and final value of the processed tea (Burgess, 1992a). Some companies normally reject green leaf with such a large coarse fraction. In Malawi, Jose (1998) reported clonal differences in the proportion of coarse leaf above which affects quality of made tea. While the quality of made tea of clone SFS204 suffered when the coarse leaf exceeded 5%, coarse leaf up to 10% appeared to be acceptable for clones PC108 and SFS150.

The fact that the proportions of coarse leaf from the grafted and ungrafted plants were the same and were all within the acceptable factory standard, indicates that the rootstocks had no effect on the quality of green leaf as assessed by the proportion of coarse leaf.

Shoot development stage

The proportion of harvested shoots depends on the harvesting policy. Although longer harvesting interval may increase yields due to harvesting heavier shoots (Burgess, 1994b), the quality of the processed tea suffers when shoots with greater than 3 leaves and bud are harvested (Stephens and Carr, 1994). The harvesting interval therefore, has to be chosen to balance between yield and quality. In this study harvesting was carried out at an interval of two phyllochrons, which is the current recommended harvesting interval in Tanzania. The higher proportions of shoots with two leaves and a bud was unexpected, as the harvesting policy targeted at shoots with three leaves and a bud. This is mainly because during harvesting, pluckers remove all shoots protruding above the plucking table regardless of the number of leaves on them. In fact, assessing shoots protruding above the plucking surface after plucking is normally a criterion used by the harvesting supervisors to judge the quality of plucking in the field. While this criterion could be used effectively for clones with short internodes, the criterion seems to be ineffective for clones with long internodes (such as S15/10 and K35). At each harvest therefore, shoots with one leave and a bud which were expected to reach three leaves and a bud in the next harvest were removed. This resulted in reduction of the proportion of shoots with three leaves and a bud.

The fact that the proportions of harvested shoots in each size category from the grafted and the ungrafted plants were the same suggests that the rootstocks had no effect on the shoot growth rates of the scions.

Shoots with more than three leaves and a bud were found to have a detrimental effect on the quality of the manufactured tea (Jose, 1998; Owuor, 1989; Stephens and Carr, 1994). The proportion of such shoots was less than 1%, and therefore unlikely to affect the quality of the processed tea. On the basis of the shoot development stage at a given harvesting policy therefore, the rootstocks have no effect on the quality of the green leaf harvested.

Apart from the green leaf quality assessment using the parameters described above, the green leaf harvested from this experiment was sold to the nearest commercial company for processing. The leaf was subjected to the standard factory procedures of quality control. Over a period of four years, no leaf was rejected for not meeting the factory standards, which confirms that all rootstocks tested had no effect on the quality of green leaf harvested as assessed by the composition of harvested shoots.

CONCLUSIONS

The rootstocks tested had no effect on the composition of harvested shoots. Since the composition of harvested shoots determines the green leaf quality, it implies therefore, that the rootstocks did no affect the quality of the green leaf harvested.

The number of shoots per kilogramme of green leaf (1,300 shoots kg^{-1}) from scion clone K35 was higher than scion S15/01 (1,200 shoots kg^{-1}). Similarly, in the driest plots rootstock PC81 increased the number of harvested shoots kg^{-1} of scion clone K35 by 18%, which implies that rootstock PC81 reduced the shoot fresh weight of scion clone K35. Nevertheless, the number of shoots per kilogramme of green leaf from all rootstock/scion combinations was within the acceptable factory standards.

The mean proportions of total fresh weight of harvested shoots comprising broken and coarse leaf were in the range 34 – 40% and 1.6 – 2.5% respectively.

CHAPTER 7

BUSH MORPHOLOGY

INTRODUCTION

Shoot population density is one of the three main components that are considered to determine the yield of tea (Squire and Callander, 1981; Stephens and Carr, 1994). The other two components of yield are the mean shoot dry mass and the time taken for an axillary bud to grow into a shoot suitable for harvesting. Previous work has shown that several factors influence these components of yield. For example, shoot population density is known to vary with altitude, genotype, nutrition, drought and temperature (Ng'etich and Stephens, 2001; Obaga *et al.*, 1989; Stephens and Carr, 1990). Similarly, the shoot dry weight varies with clone (Burgess, 1992b) and season (Cloughley, 1981). Likewise, the time taken for a bud to grow into a size suitable for harvesting depends on the climate and the weather conditions (Stephens *et al.*, 1992) and well as the altitude (Obago *et al.*, 1988).

Tea yields are also known to be determined by the size of sinks or active shoots than by the quantity of assimilate being produced by photosynthesis (Squire, 1979; Tanton, 1979). High-yielding clones have more developing shoots (i.e. sinks) to which carbohydrates can be translocated (Squire and Callander, 1981). Our understanding on how all these factors determine yields can be useful in assessing the yield potential of new clones and composite plants. The knowledge can also be useful in defining criteria for selecting high-yielding clones and composite plants.

In a composite plant, where two cultivars that are genetically different are grafted, the growth of the resultant plant depends on the way the rootstock growth affects the growth of the scion and *vice versa.* In a crop like tea where the shoots are the harvestabe part of the plant, if the resultant growth of the composite plants increases shoot numbers without decreasing shoot weight, then it is likely to increase yield. This view has been supported by Kayange *et al.* (1981) who found that rootstock MFS87 increased the yields of scion clones PC1 and SFS204 by increasing shoot numbers.

Similarly, Nyirenda and Kayange (1984) found strong interrelationships between stem circumference, number of branches and yield. The authors reported that high-yielding composite tea plants produced thicker stems than those of the ungrafted plants, suggesting that the yield increase obtained from the composite plants might be due to the rootstock effects on the stem diameter, number of branches and shoot numbers of the scion. The number of branches and/or the nature of branching (upright or spreading) determine the ground cover development and therefore the shoot numbers and yields particularly in the first years after field planting.

In this chapter, the effects of rootstock and irrigation on the bush morphology as assessed by crop cover development, shoot population density (m^{-2}), stem diameter and number of branches are examined. Similarly, since the yield of tea depends on the number of shoots that are actively growing (Matthews and Stephens, 1998), the effects of rootstock on the proportions of both actively growing and dormant shoots are also determined.

METHODOLOGY

Crop cover

To investigate the effects of rootstock on the development of ground cover as an indicator of field performance, measurements were taken from all 120 plots in the experiment (full details in Chapter 3). Between January and May 1997, data were collected monthly from one bush per plot. From June 1997, to improve the precision of the estimate, two bushes in each plot were measured monthly. After three years in the field, there was little change in ground cover within a month, and therefore measurements were taken at three months interval from June 1999.

The plants were planted at a spacing of 1.2 x 0.8 m. A wooden frame of dimensions equal to the plant spacing, containing 0.01 m^2 grid squares was placed at the centre of the selected bushes and each square was examined separately. If leaves covered less than 25% of the area of the square there was no count, 25 - 75% corresponds to one count and over 75% corresponds to two counts (Burgess, 1992). These percentages are based on visual assessment. The counts were converted into percentages as follows:

$$\text{Crop cover (\%)} = \frac{count}{192} \times 100 \qquad 7.1$$

where the figure 192 is the maximum count if the bush completely covers the ground, which is equivalent to an area of 0.96 m^2.

Shoot population density

In March 1997, 13 months after field planting, shoot population density was assessed by counting the total number of plucking points per bush. One bush per plot from all 120 plots in the experiment was sampled. From January 1998, when the plants had reached a mean ground cover of 75%, the shoot population density was assessed by the number of shoots per unit area that remained on the bush two to three days after harvest using the method described by Stephens and Carr (1994). The numbers of actively growing and dormant shoots per bush within an area of 0.1 m^2 quadrant placed at the centre of bushes were counted. Shoots were counted at the centre of the bush because previous work has shown that shoot numbers are larger near the centre of the bush than around the edges (unpublished data), which implies that most of the shoots are harvested at the centre of the bush. Shoots were counted in a smaller area (0.1 m^2) because sample areas bigger than this becomes difficult to ensure that all shoots are counted. This small sample area however, may tend to overestimate the overall shoot population density (m^{-2}).

Stem diameter

The initial plan was to measure the stem diameters above and below the graft union, to investigate if there are any differences. This however, was not possible due to the fact that to some plants it was difficult to identify the exactly point of the graft union. The stem diameters therefore were measured at the ground level using a vernier caliper. Data were collected on 28 September 2000 (4 – 5 years after field planting), from the same plants on which crop cover measurements were made for direct comparison.

Since the graft unions of some plants were not easily identified visually in the field, plants were harvested to assess the internal tissue structure/arrangement. A similar assessment made in apple composite plant at Horticulture Research International, U.K, showed differences in tissue structure/arrangement above and below the graft union (personal observation). One plant from each of the two scion clones grafted onto rootstock PC81 in the fully irrigated plots was harvested from the observation plots. Stem pieces that include the graft union were cut and left to air-dry. After drying, a vertical section cut through the graft union was made to assess tissue structure above and below the graft union.

Number of branches

To study the effects of rootstock on the number of branches of the scion, three bushes from each rootstock/scion combination in the fully (I_5) and partially (I_2) irrigated, and in the unirrigated (I_0) plots were sampled between 4 and 9 December 2000. Three irrigation treatments were chosen to minimise the time and labour requirements, as the whole exercise of counting branches in the field was difficult and time consuming. In each bush, the total number of branches at 0.45 m above the ground level was counted. This height was chosen because it is the expected pruning height when the plants are due for pruning.

For all data collected, analyses of variance were carried out to ascertain if there were differences between treatments. Similarly, regressions were carried out to test for the interrelationships among stem diameter, number of branches and shoots population density.

RESULTS

Crop cover

During the period of January 1997 to May 1998, none of the rootstocks had a significant effect on the ground cover development. The proportions of ground cover from the two scions however, were significantly different. In January 1997, 12 months after field planting, across all treatments, the ground cover of scion clone S15/10 was 22%, compared with 17% from scion clone K35. The crop cover of the grafted plants of scion clones S15/10 and K35 were 23 and 18% respectively. The corresponding values for the ungrafted plants were 18 and 15% (Figure 23).

Between January 1997 and January 1998, although not differing significantly, the proportions of ground cover of the ungrafted plants of scion clone S15/10 were consistently lower than those of the grafted plants (Figure 23 a). By the end of May

1998 (28 months after planting), the mean ground cover of the grafted plants of scion clone S15/10 was in the range 91 – 93%, which was similar to that of the ungrafted plants (90%). At the same age, the corresponding values from scion clone K35 were 85 - 90% from the grafted and 87% from the ungrafted plants.

By June 1999, 40 months after field planting, the mean ground cover (across all treatments) had reached 94%. There were again no significant rootstock effects on the proportions of ground cover of the scions. The ground cover of scion clone S15/10 (96%) however, was higher than that of scion clone K35 (92%).

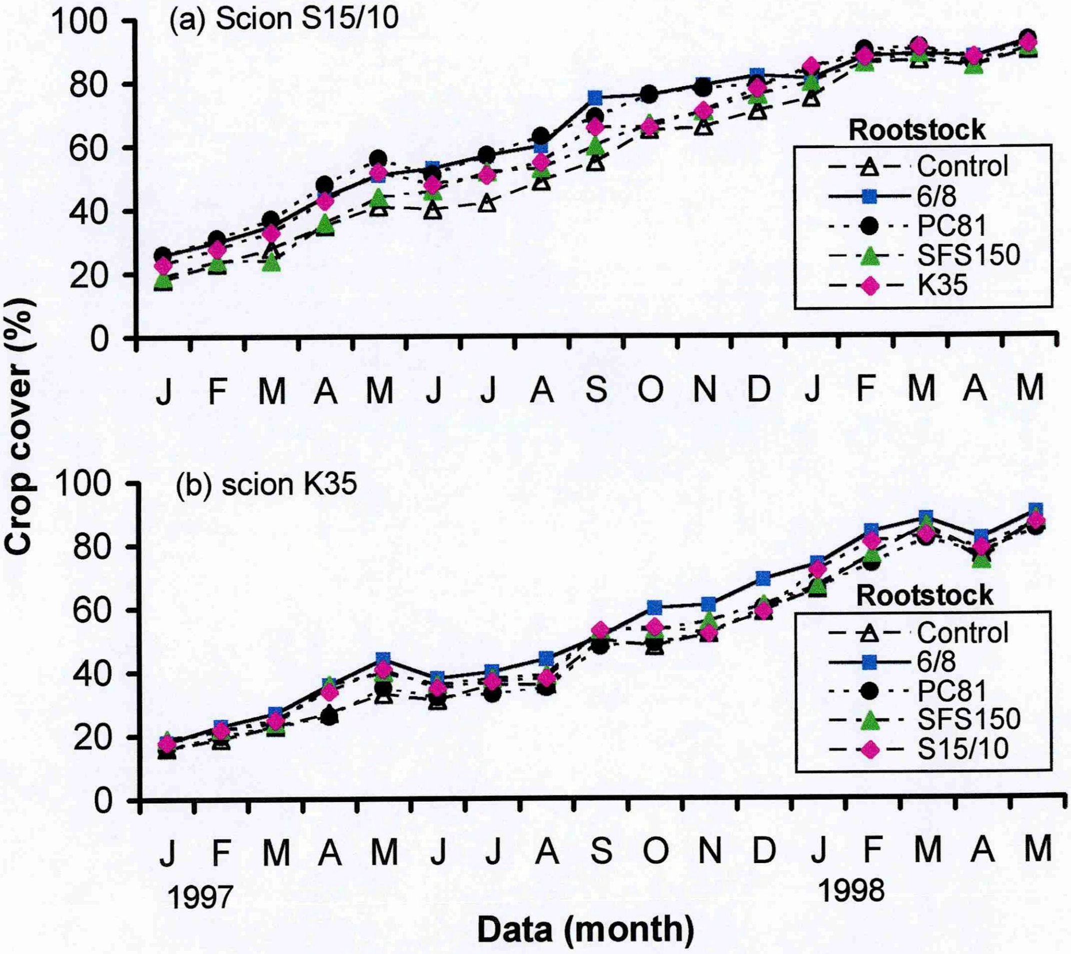


Figure 23: Effects of rootstock on crop cover development (January 1997 to May 1998) of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, PC81 and 6/8. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). "Control" refers to the ungrafted scion clones. The plants were planted in the field in February 1996.

Using the ground cover development in the first years after field planting as an indicator of field performance, then the performance of the grafted plants was generally similar to that of the ungrafted plants.

Shoot population density

Data collected on 1 March 1997 showed that the total number of plucking points per bush from scion clone S15/10 (26) was higher than that from scion K35 (20). For scion clone S15/10, the total numbers of plucking points per bush from the grafted plants were in the range 25 – 33, which were higher than those from the ungrafted plants of this scion clone (18). By comparison, the total numbers of plucking points per bush from the grafted (16 - 22) and the ungrafted (18) plants of scion clone K35 were similar.

In January 1998, when the plants had reached a mean ground cover of 75%, the mean shoot population density (268 shoots m^{-2}) from the two scions were the same. Similarly, none of the rootstocks had any effect on shoot population density of the scion. Figure 24 presents the trend of shoot population density (m^{-2}) for the period between January 1998 and May 1999. For the grafted plants of scion clone S15/10, the mean shoot population densities were in the range 254 – 271 shoots m^{-2}. The mean value for the ungrafted plants of clone S15/10 was 285 shoots m^{-2}. The corresponding population densities from scion clone K35 ranged from 255 to 286 shoots m^{-2} for the grafted and 284 shoots m^{-2} for the ungrafted plants.

During the dry season in 1998, differential irrigation treatments were applied for about ten weeks between 13 September to 20 November 1998. Data collected at the end of November 1998 showed that the mean shoot population densities of the two scions were again similar. The irrigation treatments, however, had a significant effect on the mean shoot population density of the scions. The shoot population densities from the unirrigated (328 shoots m^{-2}) and the partially irrigated (I_1) (322 shoots m^{-2}) were significant lower than those from the other irrigation treatments (379 – 407 shoots m^{-2}).

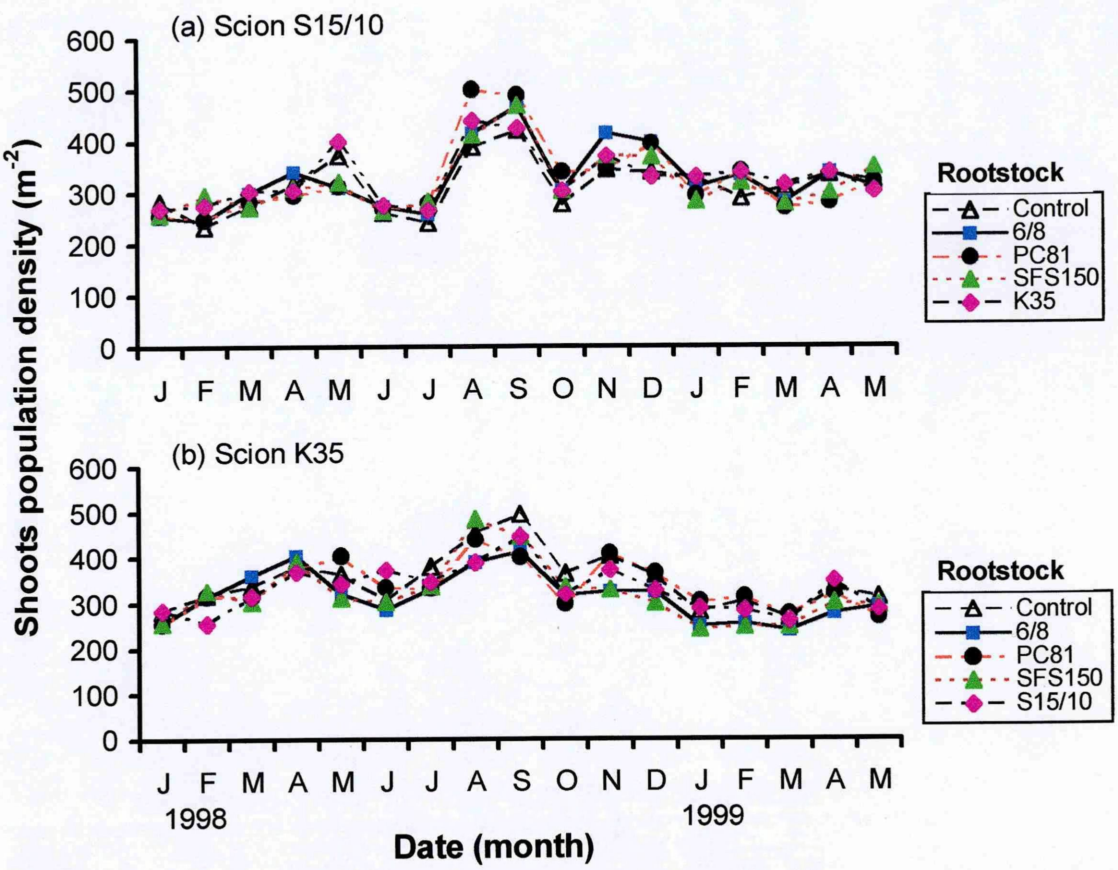


Figure 24: Effects of rootstock on shoot population density (m^{-2}) (January 1998 to May 1999) of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, PC81 and 6/8. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). "Control" refers to the ungrafted scion clones. The plants were planted in the field in February 1996.

The highest shoot population densities were recorded during the warm dry season (September to November). In September 1998, the mean shoot population density for scion clones S15/10 and K35 had reached 456 and 442 shoots m^{-2} respectively. About a year later, the corresponding shoot population densities had reached 901 and 860 shoots m^{-2}, again with no significant difference between the two scions.

Growing and dormant shoots

Data collected from January 1998 to December 2000 consistently showed that none of rootstocks had any effect on the proportions of either growing or dormant shoots. The proportions of actively growing and dormant shoots from the two scion clones however, were different. Similarly, during the dry season when differential irrigation treatments were applied, the irrigation treatments affected the proportions of growing and dormant shoots. Figure 25 presents the trend of the proportions of the growing and dormant shoots for the period of January 1998 to December 2000.

For scion clone S15/10, with the exception of the warm dry season (September to November), the proportions of growing shoots were consistently greater than those of the dormant shoots. The general trend was similar for scion clone K35, but the plants of scion clone K35 maintained greater proportions of dormant shoot throughout the year compared with those of scion clone S15/10 (Figure 25).

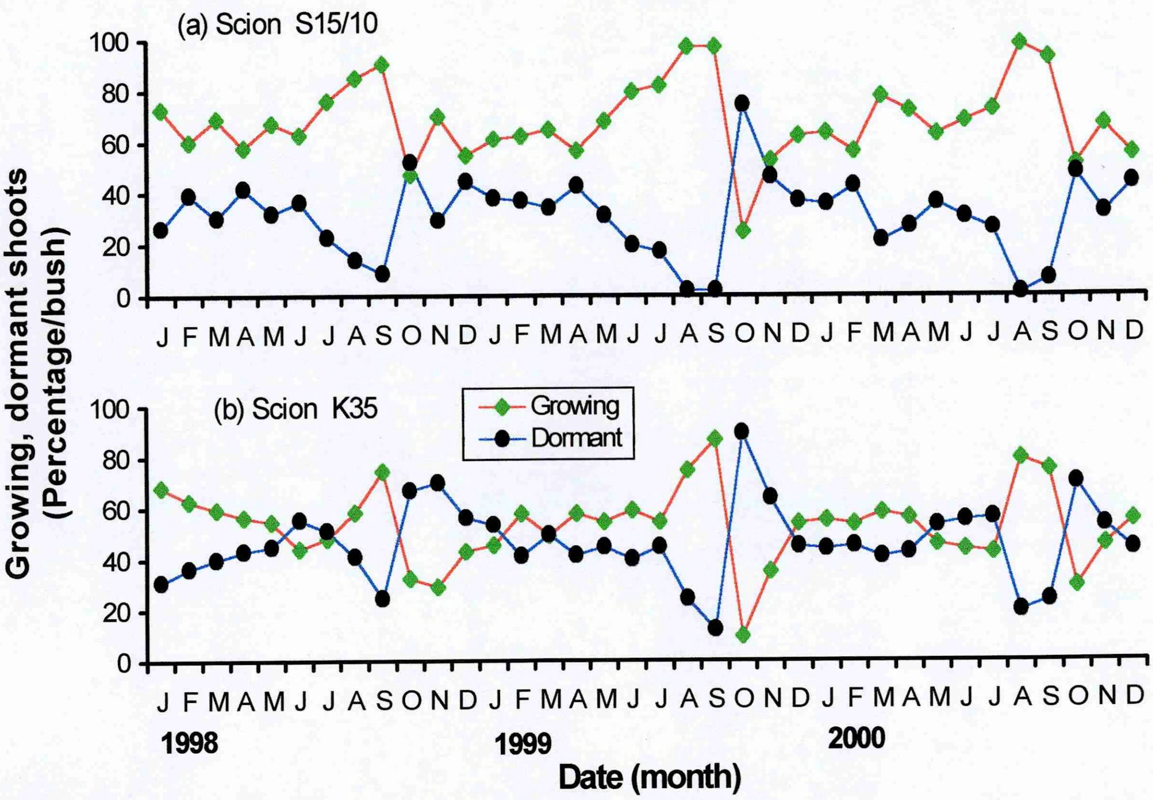


Figure 25: The proportions of actively growing and dormant shoots (January 1998 to December 2000) of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, PC81 and 6/8.

Greater proportions of shoots were actively growing during the warm dry season, with most at the end of September (about 94 and 81% for scion clones S15/10 and K35 respectively). By the end of October, the proportion of actively growing shoots of scion clone S15/10 decreased and remained fairly constant at about 60% up to May the other year. By contrast, for scion clone K35, the proportion of growing shoots remained constant (at about 47%) between October and July the next year.

Stem diameter

With the exception of the irrigation treatments in which the stem diameters were significantly different, the mean stem diameters from all other treatments were similar. The mean stem diameter (across all treatments) of the plants had reached 59 mm (at 4 - 5 years after field planting). At the same age, the mean stem diameter from the unirrigated (I_0) and the partially irrigated (I_1) treatments (about 56 mm) was similar, but lower than those from the fully irrigated treatments (59 – 60 mm). For the grafted plants of scion clone S15/10, the mean stem diameters ranged from 57 to 59 mm. The ungrafted plants of clone S15/10 had a mean stem diameter of 59 mm. The corresponding values for scion clone K35 were in the 57 – 61 mm and 63 mm for the grafted and the ungrafted plants respectively.

Structure of the graft union

Assessment of the colour and texture of the bulk of the air-dried stem pieces has shown that there were slightly differences in the colour and texture above and below the graft union for both scion clones. By contrast, when a vertical section was cut through the graft union, the colour and the internal tissue structure/arrangement above and below the grafting union were similar (Plate 4). It was therefore difficult to identify the exactly point of the graft union visually by assessing the internal tissue structure.

(a) Scion S15/10

(b) Scion K35

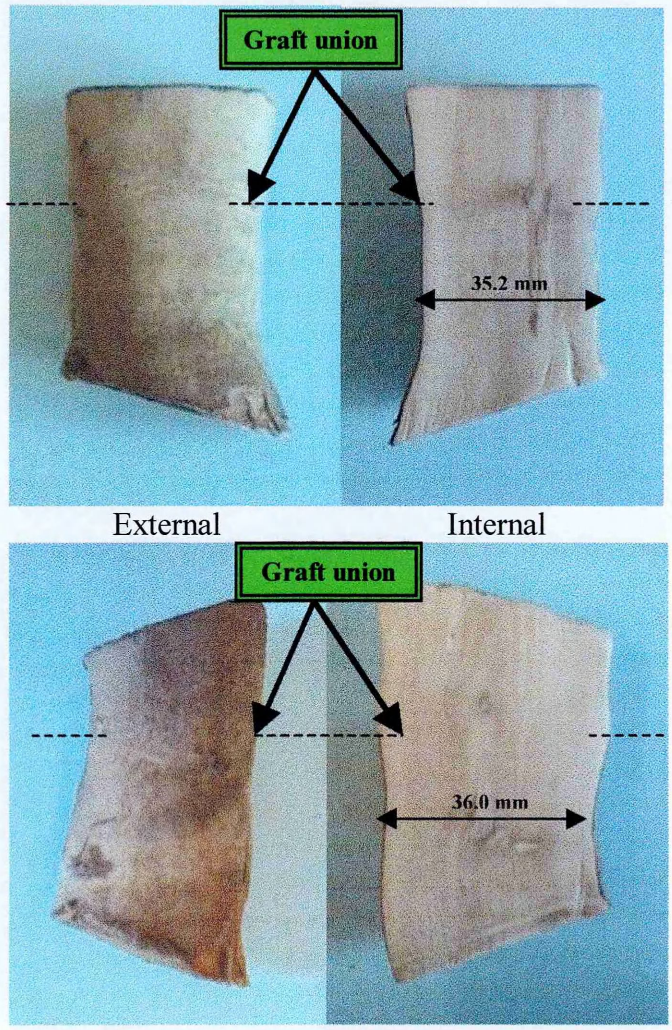


Plate 4: The external and internal texture, colour and tissue structure/arrangement above and below the grafting union of (a) scion S15/10 and (b) scion K35 grafted onto rootstocks PC81.

Number of branches

The rootstocks had no influence on the number of branches at 0.45 m above the ground. The irrigation treatments however, had a significant effect on the total number of branches. Similarly, the scion ($P \leq 0.084$) and the rootstock x irrigation treatments ($P \leq 0.089$) had a mild effect on the number of branches. Across all treatments, the mean numbers of branches of scion clones S15/10 and K35 were 82 and 92 respectively. For the irrigation treatments, the mean number of branches from the unirrigated plots (84) was lower than that from the fully irrigated treatments (89). Across rootstock and irrigation treatments, the number of branches of the grafted plants of scion clone S15/10 were in the range 73 – 87, which were the same as those of the ungrafted plants (80). The corresponding values for scion clone K35 were 88 - 101 and

103 for the grafted and the ungrafted plants respectively. In general, the mean numbers of branches from scion clone K35 tended to be higher than those from scion S15/10.

Relations between shoot population density and yield

For both scion clones, there were strong positive linear relationships between mean shoot population density (m^{-2}) and mean annual yield (Figure 26). The relationship between shoot population density and annual yield appeared to be stronger for scion clone S15/10 ($R^2 = 0.89$) than K35 ($R^2 = 0.81$).

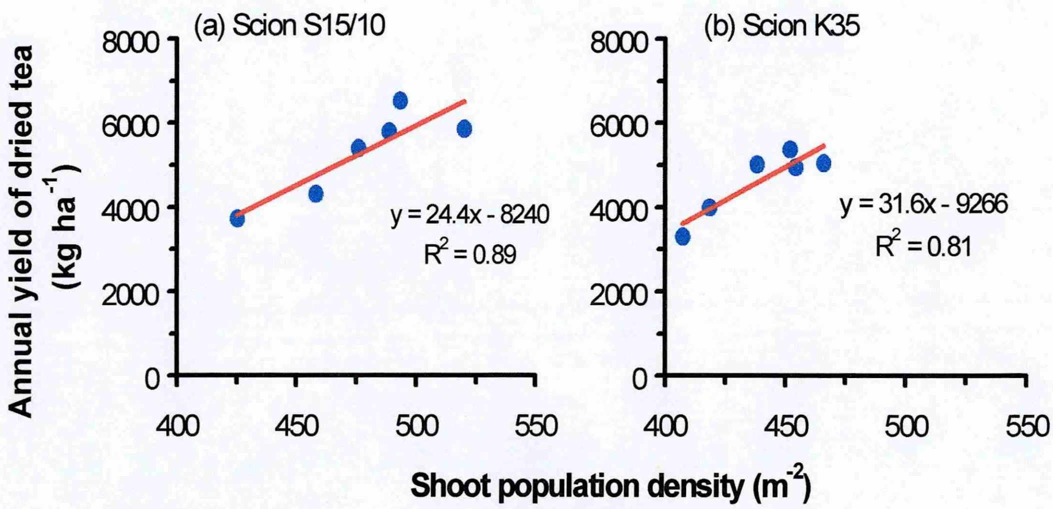


Figure 26: Relationship between shoot population density (m^{-2}) and yield for (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, 6/8 and PC81. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). The points represent yield and shoot density data from the irrigation treatments. For both scion clones, the relationships were significant.

Between stem diameter and shoot population density: although the shoot population density tended to increase with stem diameter (Figure 27), the relationships were weak for both scion clones S15/10 ($R^2 = 0.42$) and K35 ($R^2 = 0.41$).

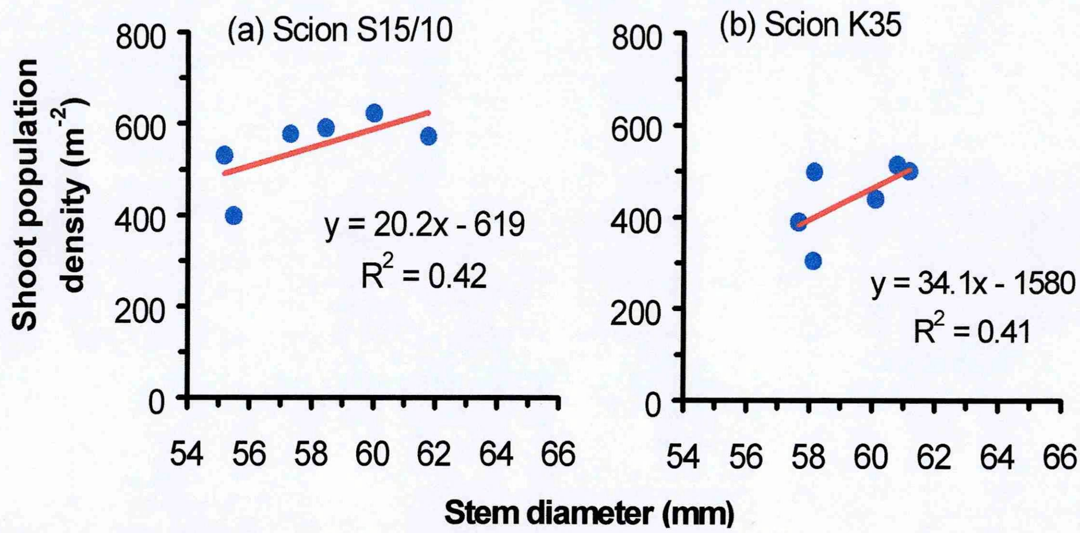


Figure 27: Relationship between stem diameter and shoot population density for (a) scion S15/10 and (b) scion K35 grafted onto rootstocks SFS150, 6/8 and PC81. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). The points represent shoot density and stem diameter data from the irrigation treatments. For both scion clones, the relationships were not significant.

Similarly, there were only weak relationships between stem diameter and number of branches as well as number of branches and shoot population density for both scion clones (Table 11).

Table 11: Summary of the relations between shoot population density and annual yield, stem diameter and shoot population density, stem diameter and number of branches; and number of branches and shoot population density of scion clones S15/10 and K35 grafted onto rootstocks SFS150, 6/8 and PC81.

Variables	Relationship
Shoot population density (m^{-2}) & annual yield (kg ha^{-1})*	S15/10: Y = 24.4(s.e.7.804)x – 8240(s.e. 372.11); R^2 = 0.89 K35: Y = 31.6(s.e. 7.756)x – 9266(s.e. 341.80); R^2 = 0.81
Stem diameter (mm) & shoot population density (m^{-2})*	S15/10: Y = 20.2(s.e. 11.740)x - 619(s.e. 68.79); R^2 = 0.42 K35: Y = 34.1(s.e. 20.50)x –1580(s.e. 121.93); R^2 = 0.41
Stem diameter (mm) & number of branches*	S15/10: Y= -8.0(s.e. 0.901)x + 128(s.e. 52.18); R^2 = 0.16 K35: Y = 1.3(s.e. 1.20)x + 13.1(s.e. 7.035); R^2 = 0.24
Number of branches & shoot population density (m^{-2})*	S15/10: Y= -7.9(s.e. 3.310)x + 1088(s.e. 273.28); R^2 = 0.54 K35: Y= 3.4(s.e. 2.980)x + 42.2(s.e. 27.927); R^2 = 0.24

**The y variable*

DISCUSSION

Crop cover

Between January 1997 and January 1998, although not significant, the mean ground cover of the grafted plants of scion clone S15/10 was higher than that of the ungrafted plants. This result show a similar pattern to the yields obtained during the first five months (January to May 1997) of harvesting, where the grafted plants of scion clone S15/10 yielded higher than those of the ungrafted plants (Chapter 5). As mentioned earlier, the quick crop cover development of the grafted plants of scion clone S15/10 was probably due to the early imbalance between the rootstock and the scion. The inherent difficulties that clone S15/10 has in establishing when planted on its own roots could also be the reason for slow crop cover development observed from the ungrafted plants of this clone. Similar results were reported at the same site (Kigalu, 1997) and at Kericho, in Kenya (Ng'etich, 1995) where clone S15/10 had slow ground cover development in the first two to three years after planting.

The fact that the ground cover of the grafted plants of scion clone S15/10 developed faster than the ungrafted plants suggests that the rootstocks improved the field establishment of clone S15/10, though this was not supported by the statistical analysis.

Shoot population density

The higher number of plucking points per bush recorded from the plants of scion clone S15/10 compared with those of scion clone K35 (at 13 months after planting) is primarily due to the differences in ground cover development of the two scions (see above). By January 1998 (24 months after field planting) however, the shoot population densities (m^{-2}) from the two scion clones were similar. This suggests that the higher proportions of ground cover and number of plucking points observed from scion clone S15/10 in the first two years after field planting were caused by the early imbalance between the rootstock and the scion, and that the effect diminished with time.

In Mufindi, in the Southern Highlands of Tanzania, tea yields during the cool season (June to August) are mainly limited by low temperatures, which affect shoot growth and development. As suggested by Tanton (1981), uniformly small shoots are formed in this period, whilst more starch is allocated in the stem and structural roots (Stephens and

Carr, 1993). From September, when favourable growth conditions are attained, a synchronized growth phase of shoots occurs (Matthews and Stephens, 1998; Tanton, 1981). These shoots reach a size suitable for harvest at about the same time. This accounts for the highest shoot population density (m^{-2}) in September/October, and consequently the peak production normally observed during September/October in the study area.

Growing and dormant shoots

Although the trend of the mean proportions of actively growing and dormant shoots for the two scions was similar, scion clone K35 had a higher proportion of dormant shoots than scion clone S15/10 throughout the year. It is interesting to note that the proportion of actively growing shoots of scion clone K35 remained fairly constant at about 47% (ranging between 10 and 59%) for the period between October and July (Figure 25). By comparison the proportion of actively growing shoots for scion clone S15/10 remained constant at about 60% (range: 25 – 78%) between October and May.

Assessing the proportion of dormant shoots in the harvested green leaf confirmed that scion clone K35 had a higher proportion of dormant shoots than S15/10 (Chapter 6). For example during 1999/00 season, 41% of the harvested shoots from scion clone K35 contained dormant shoots compared with 25% from scion clone S15/10. Similar results were reported at the same site (Burgess, 1992b) and in Kericho (Ng'etich, 1995), where clone K35 had higher proportion of dormant shoots than S15/10 when both clones were planted on their own roots. Since similar findings were reported from two different locations with different climatic conditions, the main reason for the observed differences in the proportions of actively growing shoots between the two clones appears to be their genetical differences. The two clones seem to maintain this characteristic when used as scions.

As proposed by Tanton (1979) and Squire (1979), yields in tea are likely to be determined by the size of sinks or active shoots, the higher yield obtained from scion clone S15/10 than K35 (Chapter 5), could be attributed by the differences in the proportions of actively growing shoots of the two scions. The low proportion of actively growing shoots for scion clone K35 (even with adequate soil moisture) appears to limit its yield responses to water. This seems to be the main reason for the yields of this scion clone to have remained constant at SWDs between 0 and 130, 240, 290 mm in the second, third, and fourth year after field planting respectively (see Chapter 5). The differences in critical deficits between years are primarily due to expanding root system. Similar results were reported by Nixon *et al.*, (2001) where the critical deficit for young (5 years old) clone 6/8 (200 - 250 mm) was lower than the same clone at 22 years after field planting (400 - 500 mm). The proportion of actively growing shoots therefore can be a useful guide in selecting high-yielding clones and composite plants.

During the warm dry season, scion clone K35 had more dormant than actively growing shoots. By contrast, the proportion of dormant shoots rarely exceeded the actively growing for scion clone S15/10, which implies that majority of the shoots of scion clone S15/10 were actively growing despite of low soil moisture availability for the partially irrigated and the unirrigated plots. This could be one of the reasons for the observed differences in drought survival of the two scions during the dry season (Chapter 4). Scion clone S15/10 was worse affected by water stress because of its strong sinks due to greater proportions of actively growing shoots, which means more assimilates and therefore water were required. By comparison, scion clone K35 survived the drought better due to its weak sinks as greater proportions of the shoots were dormant, which suggests that less assimilates and hence water were required for extension growth.

As proposed by Stephens and Carr (1990), only the slow growing shoots were remained on the bushes after the peak (i.e. when the faster growing shoot have been plucked) in September or early October. These shoots arise mainly from unplucked origins, and by the nature of their position, they are likely to become dormant (Tanton, 1981). This account for the higher proportions of dormant shoots occurred in October/November (i.e. after the peak). For the unirrigated plots, the higher proportions of dormant shoots could also be attributed by the water stress.

Structure of the graft union

Assessing the structure of the graft union in the field revealed that there were no obvious differences in the stem diameter above and below the union. In fact to some combinations it was difficulty to identify the exactly point of the graft union. By contrast, as the plants mature, swelling and sometimes cracking which may result in the scions separating from the rootstocks were observed in some fruit crop composite plants

(Adriance and Brison, 1979; Hartmann and Kester, 1975). For example visual observations made (by the author) at the horticulture unit of the Sokoine University, Mororgoro, Tanzania (Plate 5) and also at the HRI, U.K. showed that the graft union of fruit crops could easily be identified.

(a) Citrus

(b) Mango

Plate 5: Graft union of (a) citrus and (b) mango composite plants at the Horticulture unit of the Sokoine University, Tanzania.

Similarly, assessing the internal tissue structure above and below the graft union (Plate 4) showed no obvious differences in tissue structure/arrangement. By comparison, a similar section made in apple composite plants at the HRI showed clear differences in tissue structure/arrangement above and below the graft union (i.e. between the rootstock and the scion). Likewise, the point of the graft union was clearly identified when a radial section was made through the graft union of other fruit crop composite plants (Hartmann and Kester, 1975). All these observations suggest that unlike in fruit crops in which the graft union may crack (i.e. separation between the scion and rootstock may occur) as the plants mature, in tea the failure of a rootstock and a scion to unit probably occurs at the early stages. Once the union has taken place it is unlikely to separate or swell as observed in fruit crops.

As proposed by Hartmann and Kester (1975), the capacity of two different plants grafted together to produce a successful union and to develop satisfactorily into a composite plant depends primarily on their close relationship. A rootstock and a scion that are closely related are likely to grow into a composite plant when grafted together than those which are not closely related. The differences in graft incompatibility between the fruit crops and tea could be due to the differences in the degree of closeness between rootstocks and scions in tea and fruits crops, suggesting that there are much closer relationships genetically among tea cultivars than in fruit crops.

Although the mechanisms involved in the graft incompatibility observed at a certain stage of growth in fruit crops are not clear understood, Adriance and Brison (1979) grouped the possible mechanisms into anatomical and physiological incompatibilities. While the anatomical incompatibilities refer to those related to differences in growth characteristics between a rootstock and a scion, the physiological incompatibilities refer to those related to inability of a rootstock adequately to supply a scion with necessary amount of material required for normal functioning and *vice versa*. Both anatomical and physiological incompatibilities are likely to occur if the two plants joined together are less related genetically.

The age differences between the rootstocks and the scions at the time of grafting could also cause incompatibility. A rootstock and a scion can unit and form a successful, but weak union, which will result in graft incompatibility later. With the exception of top working (i.e. grafting onto existing bushes in the field), in tea cuttings of about the same age are normally used during grafting in the nursery (i.e. mother bushes for the rootstocks and the scions are normally pruned at the same time). This suggests that tissues of the same age are likely to form strong union than those of different age.

Wind can play a major role on weakening the graft union of a composite plant. The magnitude of the effect depends on the height above the ground. Unlike most of the fruit crops, which can grow to over 1.5 m, tea is normally maintained at heights less than 1.5 m above the ground. These differences in height therefore suggest that wind can have more effects on weakening the graft unions of fruit trees composite plants than tea. However, this would result in plant failure, but would not necessarily cause cracking or swelling of the graft union.

Yield components

As summarised in Table 11, only shoot population density and yield had a strong relationship. Similar results were reported by Matthews and Stephens (1998) for clonal tea and by Nyirenda and Kayange (1984) for composite tea plants. Nyirenda and Kayange, also found strong relationships between stem circumference, number of branches and yield. However, such relationships were found to be weak in this study. The main reason for these different findings is that in their work, both the rootstocks and the scions influenced the stem thickness and branching, whereas in this study none of the rootstocks and the scions had any effect on the stem diameter and the number of branches. This suggests that these relationships depend on the rootstock/scion combinations used.

The lack of significant effect of rootstocks on the yields of the scions (see Chapter 5) therefore, could be attribute by the failure of the rootstocks to influence the stem diameters and the branching, and hence the shoot numbers of the scions.

CONCLUSIONS

With the exception of the number of plucking points during the first year after field planting, where the rootstocks increased this attribute for scion clone S15/10, none of the rootstocks had a significant effect on the crop cover, stem diameter, number of branches and shoot population density of the scions. As assessed by these attributes therefore, the rootstocks had no effect on the bush morphology of the composite plants.

Soil water availability affected both the numbers of branches at 0.45 m above the ground and the stem diameters at the ground level. The number of branches and the stem diameter from the unirrigated plots were smaller than those from the fully irrigated treatments.

At 2 years after field planting, the shoot population densities (m^{-2}) from the plants of the two scions were similar. The proportions of actively growing shoots of the two scion clones however, were different. Throughout the year, the mean proportion of actively growing shoots (70%) from scion clone S15/10 was higher than that of scion clone K35 (53%).

The shoot population density (m^{-2}) and the annual yield had a strong relationship for both scion clones. By contrast, the relationships between stem diameter and shoot population density, stem diameter and number of branches as well as number of branches and shoot population density were weak for both scions.

CHAPTER 8

ECONOMIC ANALYSIS OF USING COMPOSITE TEA PLANTS IN TEA PRODUCTION

INTRODUCTION

Although the areas planted with composite tea plants in Eastern and Central Africa and elsewhere are small, the tea industries in many tea growing regions are aware of the possible potential that composite plants can play in tea production. Growers will not, however, adopt this technology unless they perceive the benefits to be greater than the costs. The cost and the technical difficulties in producing plants as well as the lack of criteria to select rootstock/scion combinations are the main factors limiting the rate of adoption of composites by the tea industry.

Tea growers believe that the technique required to produce composite plants is labour intensive (Nyirenda, 1995), and therefore the cost of producing plants is higher than with the traditional method. This means that growers feel that it may take longer to recover the money invested in producing plants by grafting. This belief however, has not been supported by any work to quantify the cost differences between the two methods and compare with the benefits. There is a need therefore to assess the costs and benefits of using composite plants in tea production. This assessment will evaluate the role (if any) that composite plants can play in increasing the profitability of the tea industry, and maybe to increase the rate of adoption.

To this end, this chapter reports the economic analysis of using plants produced by grafting (composite plants) and by the conventional method under both large and small-scale tea production. The benefits and payback periods as well as the break-even points for the two methods of producing planting materials are compared. Likewise, the additional cost of producing plants when growers opt to use composites rather than the conventional plants is quantified.

METHODOLOGY

As some of the costs and revenue structures for the commercial companies and the smallholders are different, the economic analysis covers the two sectors separately.

Commercial companies

The main cost structures when planting materials were produced by grafting and by the conventional method in the nursery and in the field as well as during processing were identified. To determine the cash flows for both methods, the revenue/cash inflows from selling the processed tea were calculated. Yield data (kg ha^{-1} of made tea) for the period between January 1997 and May 2001 were used. The yield data were scaled down to match the yield levels obtained in the commercial estates as the yields from the estates are normally lower than those from experiments. The yields obtained from the best estates in the Southern Highlands of Tanzania are about 75% of those obtained from the experimental plots. To reflect the commercial reality therefore, the yields used for the economic analysis were reduced by 25%. Since there were no yield benefits of using composite plants when grown under well-watered conditions (see Chapter 5), the economic analysis will only cover the rainfed conditions.

Costs

To quantify the benefits in any production system, the total costs and revenue have to be determined. The costs of using planting materials produced by both methods were estimated. The costs involved were divided into three major groups: nursery, field and processing costs.

Nursery

The nursery costs consist of all costs from preparation of mother bushes up to when the plants were ready for planting in the field. However, costs such as soil preparations, irrigation, weeding and fertilizer application in the nursery were assumed to be the same for both methods, and therefore were not included.

Pruning of mother bushes: to produce a composite plant (by clef grafting) two single node stem pieces are normally used compared with the conventional method where one single node stem piece is used. The number of tea bushes to be pruned to produce composite plants therefore, was assumed to be twice that of the conventional method.

This implies that the cost incurred in pruning mother bushes for producing composite plants is twice that of the conventional method.

Loss of revenue

The loss of yield due to pruning the mother bushes for cuttings means that growers will lose revenue from the pruned area. This loss of revenue was determined by assuming annual yield loss in the year of pruning. As the number of bushes to be pruned when producing composite plants is twice that of the conventional plants (see above), the loss of revenue when producing composites was estimated to be twice that of the ungrafted plants.

Grafting: as mentioned earlier (see Chapter 2), the labour cost and the technical difficulties in producing composite plants are among the main factors limiting the commercial use of composite tea plants. For example, Nyirenda (1995) found that one man can only produce (by cleft grafting) 420 composite plants a day while the same person can produce 1,250 unrooted cuttings per day using the conventional methods.

The lower success rate achieved in the nursery is another limiting factor in the adoption of composite plants by the tea industry. For example, in Malawi, a success rate of 60% was reported in the early grafting work (Scarborough, 1981). Similarly, in this study, the overall mean success rate obtained from the grafted plants (59%) was significantly lower than that of the ungrafted plants (91%). These low success rates were mainly caused by the inexperience of the grafters. In recent years, a mean success rate of 79% (ranging between rootstock/scion combinations 62 – 95%) was commonly achieved in the commercial nurseries in Malawi (Nyirenda and Mphangwe, 2000). A similar mean success rate (76%) was reached in the second attempt to graft tea plants at Ngwazi Tea Research Station (unpublished data). This suggests that with skilled grafters high success rates comparable to those of the ungrafted plants can be attained.

Estimating the nursery costs using the success rate obtained in this study therefore would overestimate the costs because the figure appears to be not representative if skilled grafters were used. For that reason, a mean success rate of 79% achieved in the commercial nurseries in Malawi, which was similar to that obtained in the recent work at Ngwazi Tea research Station was used. It is useful to note however, that using this figure would slightly overestimate the nursery costs, because higher success rates than this can be achieved. For the conventional method, a mean success rate of 91% was used, which is the value obtained from the ungrafted plants in this study and also it is within the range of values achieved by the commercial nurseries in the Southern Highlands of Tanzania.

Field costs

Harvesting is one of the most labour intensive field operations in tea production. It was estimated that the harvesting costs represents 30 - 40% of the total field production costs on estates in Tanzania and elsewhere in Eastern and Central Africa (Burgess, 1992a; Goldsmith and Kilgour, 1999). Harvesting will have additional cost per unit area when using composite plants rather than the conventional plants (ungrafted) if the yields from the grafted plants are higher than those from the ungrafted plants. This is the cost tea growers have to incur to harvest the increased yields from the composite plants. Since the tea pluckers in the Southern Highlands of Tanzania are commonly paid based on the number of kilogramme of green leaf they harvest, the harvesting cost was assumed to be proportional to the percentage yield increase/decrease. The cost of harvesting composite plants therefore was estimated to be higher/lower than that of the ungrafted plants by the same percentage as that of the yield increase/decrease. This assumption however, may not give a good estimate of the cost when the pluckers are paid on the basis of the time and/or a fixed rate per day.

All other field costs per unit area such as weeding, fertilizers application and irrigation for the grafted and the ungrafted plants were assumed to be the same, and therefore were not included in the annual cost outlays.

Processing cost

The processing costs were estimated using the commercial figures from Brooke Bond Tanzania Limited's Lugoda factory, where the green leaf from the experiment was processed. At this factory the processing cost was estimated to be US \$ 0.16 kg^{-1} of made tea (Salim, 2000). This figure was used to calculate the processing costs.

Miscellaneous costs

Apart from the costs described above, the tea growers are likely to incur other costs when using composite plants. These costs include the cost of transporting the additional cuttings needed to produce composite plants from the field to the nursery (i.e. the number of cuttings needed to produce composite plants ha^{-1} is twice that of the ungrafted). Similarly, there were additional costs of removing the buds/shoots growing from the rootstocks in the nursery as well as removing the suckers (if any) in the first years after field planting. These costs were proportionally small and therefore were ignored.

Revenue

The main source of revenue was the selling of the processed tea from the plants produced by the two methods. Since the value of made tea depends on the quality, the values of the processed tea from the two methods would be different if grafting a scion clone onto a rootstock affects its quality. The previous studies however, demonstrated that the rootstock had no significant effects on the quality of made tea of the scion (Bore *et al.*, 1995; Kayange *et al.*, 1981).

The quality of made tea from the two scion clones (i.e. S15/10 and K35) when planted on their own roots (ungrafted) is known to be different. Clone K35 produces better quality tea than clone S15/10 (Burgess, 1992b; Burgess, 1994a; Carr, 1995; Ng'etich *et al.*, 1995). Despite this difference in quality however, Burgess (1994a) assessed the values of made tea from the two clones, and found that the values did not differ significantly. These findings suggest that the same value of the processed tea can be used to calculate the revenue for both the grafted and the ungrafted plants.

Figure 28 presents the average prices of made tea (US \$ kg^{-1}) of Tanzanian teas at Mombasa auction for the period between May 1995 and February 1999. During this period, there were huge variations (US \$ 0.61 – 2.23 kg^{-1}) in the prices of tea at the auction. These variations have major effects on the payback period and on the overall benefits due to grafting. The choice of the production system therefore, would be influenced by the market prices.

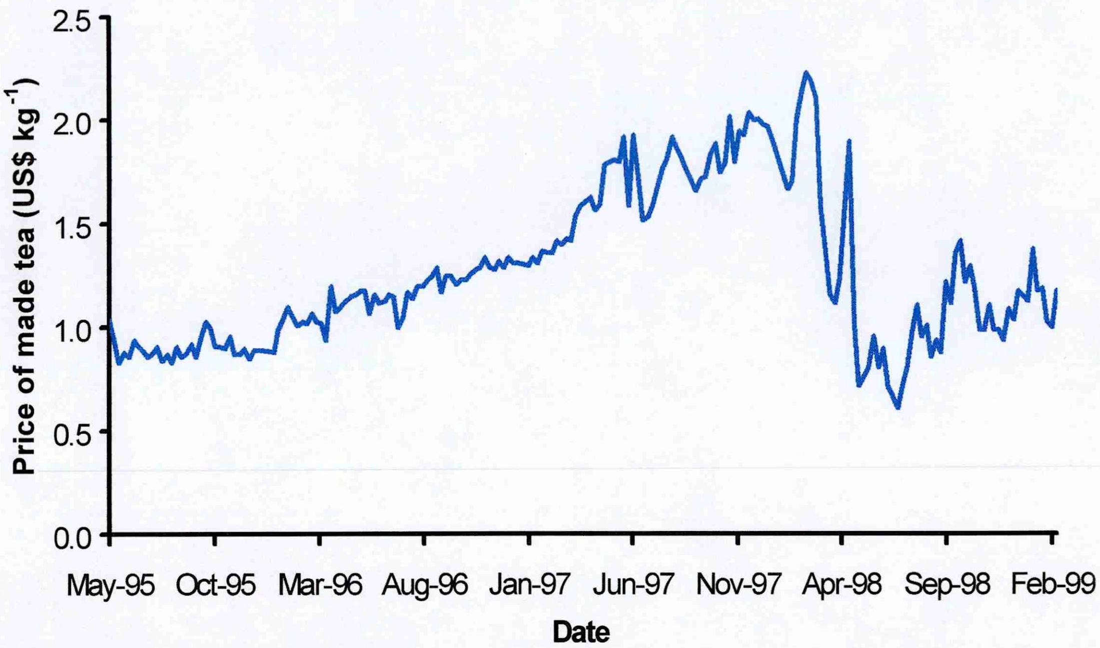


Figure 28: Average Tanzanian tea price (US \$ kg^{-1}) at Mombasa auction for the period May 1995 to February 1999.

To take into account these variations in the market prices, the lowest (US \$ 0.61 kg^{-1}) and the highest (US \$ 2.23 kg^{-1}) prices fetched by the Tanzanian tea at the auction for the period between May 1995 and February 1999 were used to calculate the revenue from selling the processed tea from both the grafted and the ungrafted plants.

Smallholders

For the smallholders, the cost structures described above apply with the following exceptions: there were no processing costs incurred, as smallholders sell green leaf to the nearby factories. That is, the source of revenue for the small-scale farmers was the selling of green leaf not the processed tea as for the commercial growers. The green leaf price was estimated to be US \$ 0.11 kg^{-1}. The cost of harvesting was calculated based on the average harvesting rate (mainly involving family labour) of 40 kg per day (Nyanga *et al.*, 2000). The manday rate (US \$ 1.31 per day) was estimated on the basis of civil servants minimum wage.

Unlike in the commercial estates where the yields were considered to be 75% of the experimental yields, for the smallholders the yields were assumed to be 50% of those from the experimental plots.

Probability of achieving a given yield increase

Although statistical analysis showed no significant yield difference between the grafted and the ungrafted plants, the yields from some of the grafted plants were consistently higher than those from their respective scion clones when planted on their own roots. For example, throughout the period of yield recording, the yields of scion clone S15/10 grafted onto rootstock 6/8 were higher than those from the ungrafted plants. A similar yield trend was observed for scion clone K35 when was grafted onto rootstock SFS150. For that reason, it was useful to calculate the probability of achieving yield increase sufficient to make the investment worthwhile from these combinations.

Assuming that the probability of achieving a given yield increase conforms to a normal distribution with a mean and standard deviation calculated from observed yields, the probability of achieving an annual yield increase greater than a given yield increase was computed. A given yield increase referred here can be the minimum yield increase the individual tea growers required to cover the extra cost of producing plants by grafting and/or to justify the use of composites estimated based on their production costs and the market price.

RESULTS

Commercial companies

Table 12 summarises the detailed estimates of the labour requirements and costs of producing planting materials by grafting and by the conventional method. Once the plants were produced, all other nursery costs (per unit area or per plant) such as soil preparation, weeding, irrigation and fertilizer application were assumed to be the same for the two methods and therefore excluded from the costs in Table 12.

While ten mandays are needed to make enough cuttings for one hectare using the conventional method, 32 mandays are required to graft plants enough for the same area. Based on the assumptions in Table 12, the cost of producing plants by grafting was about three times higher than that of conventional method.

Table 12: Summary of detailed estimates of the cost of producing plants (US $ ha^{-1}) by grafting and by the conventional method under commercial nurseries.

Category	Grafting	Conventional method
Nursery success rate (%)	79	91
Total number of plants (ha^{-1})*	13,235	11,923
Mandays needed to produce plants (ha^{-1})**	32	10
Manday rate (US $ day^{-1})	2.15	2.15
Labour cost for producing plants (US $ ha^{-1})	69	22
Cost of pruning mother bushes (US $)	2	1
Loss of revenue due to pruning the mother bushes (US $)	94	42
Total nursery cost (US $ ha^{-1})	**165**	**65**

**The total number of plants produced calculated based on plant population of 10,417 ha^{-1} adjusted for the nursery success rates accordingly. Additionally, 5% of the adjusted number of plants ha^{-1} was added for field infilling.*
*** The mandays were based on one person (experienced grafter) making 420 and 1,250 unrooted composite plants and ungrafted cuttings per day respectively (Nyirenda, 1995).*
**** Pruning cost was estimated at US $ 0.014 per bush (Malavanu, 2001).*

Table 13 presents the cash flows for both the grafted and the ungrafted plants for the period between 1995/96 (year 0) and 2000/01 (year 5). The cash flows were calculated using yield data from the unirrigated plots. Mean yields across scion and rootstock treatments for the grafted plants and mean for both scion clones for the ungrafted plants were used.

During the period between 1995/96 (year 0) and 2000/01 (year 5), the cumulative benefit from the grafted plants when the price of made tea was US $ 2.23 kg^{-1} (US $ 15,282 ha^{-1}) was about 6% higher than that of the ungrafted plants (US $ 14,400 ha^{-1}) (Table 13 a). By contrast, at the minimum price of made tea (US $ 0.61 kg^{-1}), the cumulative benefit from the grafted plants was 15% lower than that from the ungrafted plants (Table 13 b).

At the maximum made tea price (US $ 2.23 kg^{-1}), the revenue outlays exceeded the costs (payback period) for both methods at year 2 (i.e. the second season of harvesting), but the extra revenue generated at this period from the grafted plants was US $ 431 ha^{-1} more than that generated from the ungrafted plants. Likewise, the overall benefit due to grafting at this made tea price occurred in year 2 (Table 13 a). By the end of year 5, the overall cumulative benefit due to grafting was US $ 882 ha^{-1} when the price of made tea was US $ 2.23 kg^{-1}.

Table 13: Discounted cash flow for the plants produced by grafting and by the conventional method between 1995/96 (year 0) and 2000/01 (year 5) for the commercial companies. The revenue calculated at the maximum and the minimum made tea prices of (a) US \$ 2.23 kg^{-1}and (b) US \$ 0.61 kg^{-1}. Control refers to the conventional method of producing planting materials.*

(a) US \$ 2.23 kg^{-1}

Methods	Category	Year 0	1	2	3	4	5
Control	Revenue (US \$ ha^{-1})	0	442	3,915	4,508	4,498	4,855
	Costs (US \$ ha^{-1})	65	490	799	832	809	822
	Cash flow (US \$ ha^{-1})	-65	-49	3,116	3,675	3,689	4,034
	Cumulative cash flow (US \$ ha^{-1})	**-65**	**-113**	**3,002**	**6,678**	**10,367**	**14,400**
Grafting	Revenue (US \$ ha^{-1})	0	627	4,629	4,889	4,731	4,795
	Costs (US \$ ha^{-1})	165	711	948	902	851	812
	Cash flow (US \$ ha^{-1})	-165	-84	3,681	3,986	3,880	3,983
	Cumulative cash flow (US \$ ha^{-1})	**-165**	**-248**	**3,433**	**7,419**	**11,300**	**15,282**
Overall benefits due to grafting	**Cash flow (US \$ ha^{-1})**	**-100**	**-35**	**566**	**311**	**191**	**-51**
	Cumulative cash flow (US \$ ha^{-1})	**-100**	**-135**	**430**	**742**	**933**	**882**

(b) US \$ 0.61 kg^{-1}

Methods	Category	Year 0	1	2	3	4	5
Control	Revenue (US \$ ha^{-1})	0	121	1,071	1,233	1,230	1,328
	Costs (US \$ ha^{-1})	65	490	799	832	809	822
	Cash flow (US \$ ha^{-1})	-65	-370	272	401	422	506
	Cumulative cash flow (US \$ ha^{-1})	**-65**	**-434**	**-162**	**238**	**660**	**1,166**
Grafting	Revenue (US \$ ha^{-1})	0	172	1,266	1,337	1,294	1,312
	Costs (US \$ ha^{-1})	165	711	948	902	851	812
	Cash flow (US \$ ha^{-1})	-165	-539	318	435	443	500
	Cumulative cash flow (US \$ ha^{-1})	**-165**	**-704**	**-386**	**49**	**493**	**992**
Overall benefits due to grafting	**Cash flow (US \$ ha^{-1})**	**-100**	**-170**	**47**	**34**	**22**	**-7**
	Cumulative cash flow (US \$ ha^{-1})	**-100**	**-270**	**-232**	**-189**	**-167**	**-174**

**Maximum and minimum price of Tanzanian tea at Mombasa auction between May 1995 and February 1999.*

By comparison, at the minimum price of made tea (US \$ 0.61 kg^{-1}), the payback period was delayed by one year for both methods of producing planting materials. At this price the tea producers started realising profit at year 3 (i.e. the third season of harvesting). Similarly, there were no overall benefits due to grafting when tea price was US \$ 0.61 kg^{-1}. Tea growers would still realise loss even beyond year 5 at this tea price if they opt to use composite plants (Table 13 b).

Smallholders

Like the commercial companies, the labour cost of producing plants by grafting for the small-scale tea growers was about three times higher than that of the conventional method. Table 14 summarises the detailed estimates of the labour requirements and the costs of producing plants by the two methods under small-scale nurseries.

Table 14: Summary of detailed estimates of the cost of producing plants (US \$ ha^{-1}) by grafting and by the conventional method under small-scale nurseries.

Category	Grafting	Conventional method
Nursery success rate (%)	79	*91*
Total number of plants (ha^{-1})*	13,235	11,923
Mandays needed to produce plants (ha^{-1})**	32	10
Manday rate (US \$ day^{-1})***	1.31	1.31
Labour cost for producing plants (US \$ ha^{-1})	42	13
Cost of pruning mother bushes (US \$)****	4	1
Loss of revenue due to pruning the mother bushes (US \$)	27	12
Total nursery cost (US \$ ha^{-1})	**73**	**26**

**The total number of plants produced calculated based on plant population of 10,417 ha^{-1} adjusted for the nursery success rates accordingly. Additionally, 5% of the adjusted number of plants ha^{-1} was added for field infilling.*
*** The mandays were based on one person (experienced grafter) making 420 and 1,250 unrooted composite plants and ungrafted cuttings per day respectively (Nyirenda, 1995).*
**** Manday rate estimated based on civil servants minimum wage.*
*****Pruning cost estimated based on an average pruning rate of 130 bushes per day (Nyanga et al., 2000).*

An assessment of the cash flow (Table 15) showed that small-scale tea producers would start realising profit earlier than the commercial companies. For smallholders, the payback period was in year 1 (i.e. the first year of harvesting) which was the same for both methods, compared with the commercial companies in which depending on the price of made tea, this period was in year 2 or 3, but again was the same for both methods.

Table 15: Discounted cash flow for the plants produced by grafting and by the conventional method between 1995/96 (year 0) and 2000/01 (year 5) for the smallholders. The revenue calculated from the sell of green leaf at US \$ 0.11 kg^{-1}. Control refers to the conventional method of producing planting materials.

Methods	Category	Year 0	1	2	3	4	5
Control	Revenue (US \$ ha^{-1})	0	66	564	645	668	725
	Costs (US \$ ha^{-1})	26	25	217	248	257	279
	Cash flow (US \$ ha^{-1})	-26	41	347	397	411	446
	Cumulative cash flow (US \$ ha^{-1})	**-26**	**15**	**362**	**759**	**1,170**	**1,616**
Grafting	Revenue (US \$ ha^{-1})	0	100	698	700	705	715
	Costs (US \$ ha^{-1})	73	38	269	269	271	275
	Cash flow (US \$ ha^{-1})	-73	82	429	431	434	440
	Cumulative cash flow (US \$ ha^{-1})	**-73**	**9**	**438**	**869**	**1,303**	**1,743**
Overall benefits due to grafting	**Cash flow (US \$ ha^{-1})**	**-47**	**41**	**82**	**33**	**23**	**-6**
	Cumulative cash flow (US \$ ha^{-1})	**-47**	**-6**	**77**	**110**	**133**	**127**

The small-scale farmers started to realise overall benefits due to grafting in year 2 (i.e. the second season of harvesting), but the annual benefits diminished with time. By the end of year 5, the net present value (NPV) from the grafted plants (US \$ 1,743 ha^{-1}) was 8% higher than that of the ungrafted plants, giving the overall cumulative benefit of US \$ 127 ha^{-1}. This benefit is equivalent to about 37% of the annual income of civil servants on the minimum wage.

Total yield increase necessary to make the investment worthwhile

Commercial tea producers will have to incur an additional cost of producing plants of US \$ 100 ha^{-1} when they opt to use composites rather than the conventional plants. The total yield increase required to cover this cost or rather to make the investment worthwhile depends on the production cost and the market price (i.e. US \$ kg $^{-1}$). This means that the total yield increase necessary to make the use of composites in tea production viable depends on the profit per kilogramme of made tea.

Knowing their production cost (US \$ kg^{-1}), growers can determine the profit per kilogramme of made tea and therefore the total yield increase they required to make the use of composite plants in tea production viable. Figure 29 presents the effects of the profit of the processed tea on the total yield increases necessary to make the investment worthwhile for the commercial companies.

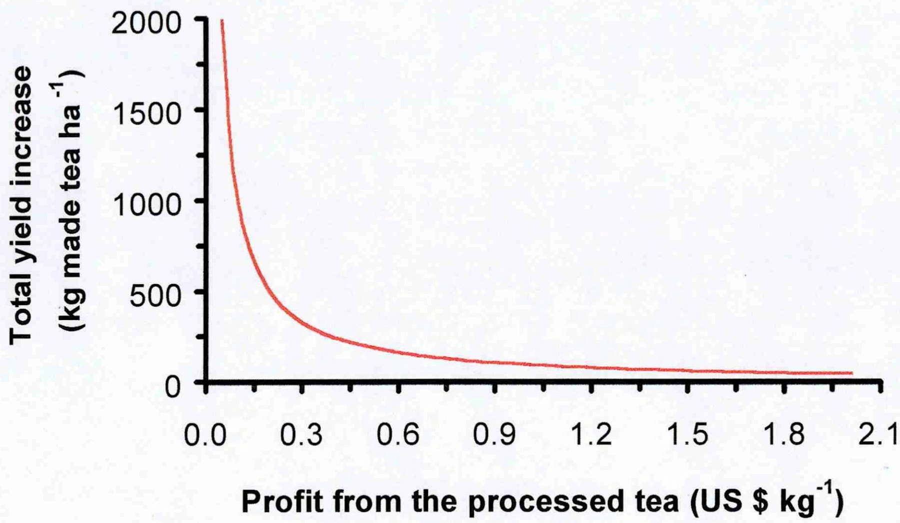


Figure 29: Effects of the profit of the processed tea on the total yield increase necessary to make the use of composite plants in tea production worthwhile when the commercial tea producers opt to use composites rather than the conventional plants.

For the small-scale growers, the extra cost of producing plants if they opt to use composites rather than the conventional plants was US $ 47 ha^{-1}. Figure 30 summarises the effects of profit from the green leaf (US $ kg^{-1}) on the total yield increase required by the smallholders to justify the use of composites in tea production.

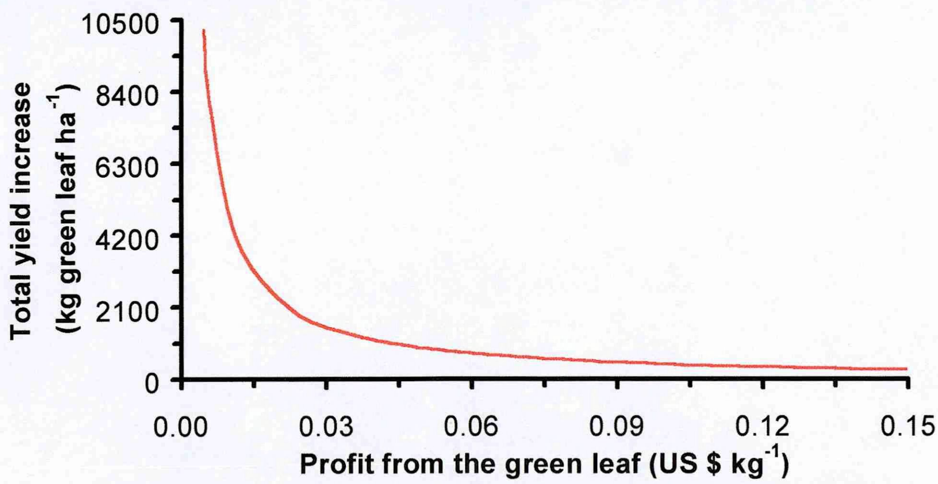


Figure 30: Effects of the profit from the green leaf on the total yield increase necessary to make the use of composite plants in tea production worthwhile when the smallholders opt to use composites rather than the conventional plants.

Like the commercial companies, the production cost and therefore the profit (US $ kg^{-1} of green leaf) at a given price is likely to vary with individual farmer. The total yield increase required to justify the use of composites in tea production would then be different among farmers.

Probability of achieving a given yield increase

Although the yields from the grafted and the ungrafted plants did not differ significantly, some of the grafted plants consistently yielded higher than their respective scion clones when planted on their own roots. These combinations include S15/10 on 6/8 and K35 on SFS150. To assist the tea growers to make decisions, the probability of achieving an annual yield increase greater than a minimum necessary to cover the extra cost of producing plants by grafting or to justify the use of composites in tea production was determined.

Figure 31 presents the probability of achieving an annual yield increase greater than a given yield increase when scion clone S15/10 was grafted onto rootstocks 6/8 and SFS150. At a given yield increase, growers can establish the chances of getting such yield. For example, if tea producers are operating at a profit of US \$ 0.5 kg^{-1}. The corresponding total yield increase is 200 kg ha^{-1} of made tea (Figure 29). The probability of getting a yield increase greater than 200 kg ha^{-1} in one year was 81% when scion clone S15/10 was grafted onto rootstock 6/8 (Figure 31). By contrast, there was low chance (probability = 47%) of getting annual yield increase greater than 200 kg ha^{-1} when the same scion was grafted onto rootstock SFS150.

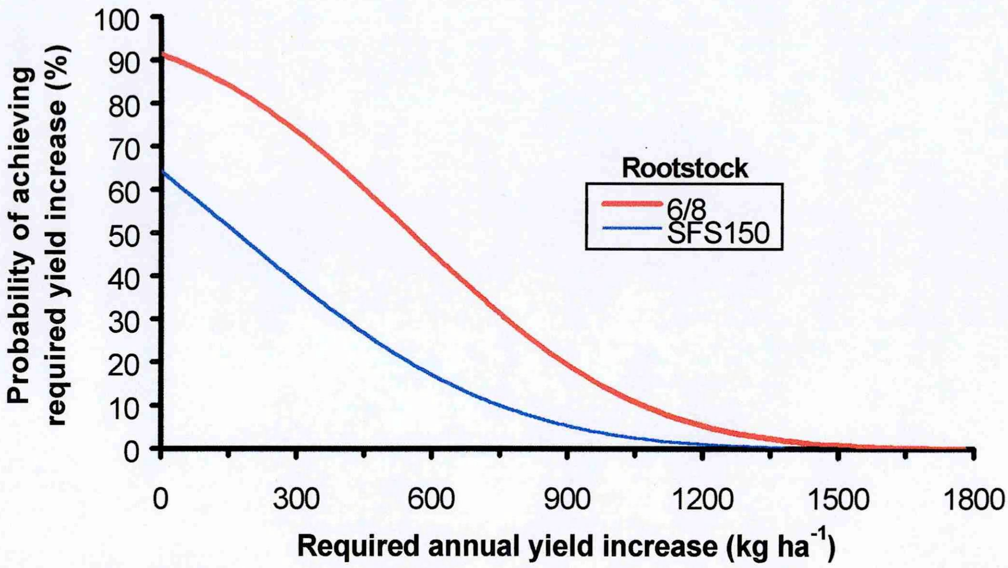


Figure 31: Probability of achieving annual yield increase greater than a given minimum yield increase when scion clone S15/10 was grafted onto rootstocks 6/8 and SFS150. A given yield increase referred here can be the minimum yield increase necessary to cover the extra cost of producing plant by grafting and/or to justify the use of composites in tea production.

Similarly, if the same minimum yield increase was required, the corresponding probability was 74% when scion clone K35 was grafted onto rootstock SFS150, but there was no chance (probability = 0) of getting such annual yield increase when scion clone K35 was grafted onto rootstock 6/8 (Figure 32).

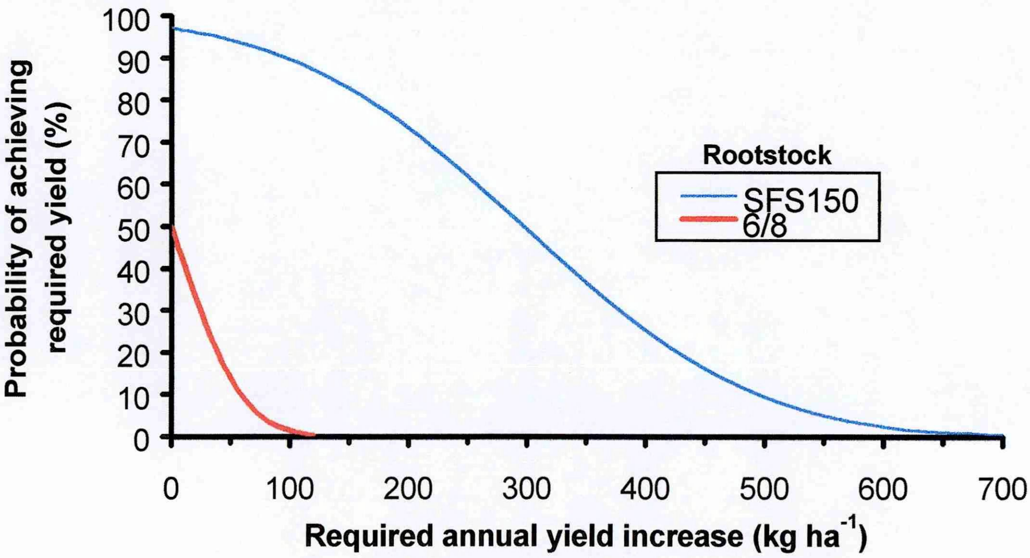


Figure 32: Probability of achieving annual yield increase greater than a given yield increase when scion clone K35 was grafted onto rootstocks 6/8 and SFS150. A given yield increase referred here can be the minimum yield increase necessary to cover the extra cost of producing plant by grafting and/or to justify the use of composites in tea production.

The probability assessment presented above when scion clones S15/10 and K35 were grafted onto rootstocks 6/8 and SFS150 respectively, suggests that there was high chance of getting the required total yield increases, making the use of these combinations in tea production worthwhile.

DISCUSSION

Commercial companies

The labour cost for producing plants by grafting was one of the main constraints in the adoption of composite plants by the tea industry. Table 12 suggests that the labour requirements (mandays) for grafting are about three times more than that of the conventional method. At a given manday rate therefore tea growers can quantify the cost of grafting.

As demonstrated in Table 13, using the mean yield (across rootstock and scion treatments for the grafted plants and mean for both clones for the ungrafted plants) from the experiment reported in this thesis, the annual benefits due to grafting diminished with time. By the end of year 5, there were no further benefits of using composite plants. Depending on the tea price, at this period however, tea growers may have realised profit from using composites in tea production. For example, at year 5, the overall cumulative benefit due to grafting was US \$ 882 ha^{-1} when the tea prices was US \$ 2.23 kg^{-1}, but when the price was US \$ 0.61 kg^{-1}, there was no overall benefit of using composite plants even beyond year 5. In fact at this price, there was an overall cumulative loss of US \$ 174 ha^{-1}.

It is useful to note that the diminishing trend of benefits in Table 13 is due to the fact that pooled mean yields from the two methods (i.e. from grafted and the ungrafted plants) were used in the financial assessment. The mean yields from some of the individual rootstock/scion combinations (see Chapter 5) such as S15/10 on 6/8 and K35 on SFS150, suggest that there were benefits even beyond year 5 from these combinations.

The period at which the tea growers would start realising profit when using composite plants has been another limiting factor to the adoption of grafting as a means of producing planting materials. Tea growers feel that by using composite plants, this period would be more than when using the conventional plants (ungrafted). This is contrary to the findings of this study, that the pay back period for the two methods of producing planting materials was very similar. Depending on the price of the processed tea the pay back period was in year 2 or 3 (i.e. second or third season of harvesting) for the commercial tea producers.

The market price of the processed tea has major effects on the cash flows of the two options of producing planting materials (Table 13). The overall benefits and the decision of the tea growers to opt to use composite plants would therefore be strongly influenced by the market price. Nevertheless, for some rootstock/scion combinations, there were higher chances of getting total yield increases greater than a minimum necessary to justify the use of composites in tea production.

Smallholders

Like the commercial companies, the cost of producing plants by grafting under small-scale nurseries was three times more than the conventional method, but the small-scale growers started to realise profit earlier than the commercial companies. This is primarily due to cheap labour paid on the basis of the minimum civil servants wage, but also smallholders do not incur processing costs as they sell green leaf. The additional cost of producing plants that the small-scale farmers have to incur when they opt to use composites rather than the conventional plants was US $ 47 ha^{-1}, which is only 47% of the cost incurred by large-scale growers.

Although statistical analysis showed no significant yield differences between rootstocks, the probability of achieving a yield increase sufficient to make the investment worthwhile was higher for some combinations such as S15/10 on 6/8 and K35 on SFS150. Similarly, the fact that some composite plants appeared to survive the drought better than the ungrafted plants (see Chapter 4) means that composites can play an important role in improving plant survival during severe drought periods. Gaps that are likely to be caused by deaths due to drought are commonly found in most of the smallholders' fields. The use of plants that would ensure survival and maintain yields during the dry seasons and therefore cash inflow is vital for the sustainability of the small-scale tea producers. Grafting to combine yield, quality and drought tolerance could be one way of producing such plants.

Total yield increase necessary to make the investment worthwhile

The total yield increase necessary to make the use of composites worthwhile varies with tea grower. This is primarily due to differences in the profit per kilogramme (made tea or green leaf) realised between growers, which is mainly caused by differences in the production cost (kg^{-1}). The difference in tea prices between companies caused by the differences in tea quality, can also make tea growers to have different profit (kg^{-1}).

Since the total yield increase required to make the use of composites in tea production worthwhile varies with tea grower, it is difficult to determine the exact figure of this yield increase. Based on their production costs however, the individual tea producers can quantify the yield increase they require to make the investment worthwhile.

As Figure 29 (for the commercial companies) and Figure 30 (for the smallholders) suggest, growers have two options to achieve the total yield increase necessary to make the use of composite plants viable. The first option is to increase the yields from the composites that will allow them to get the required total yield increase even at small profit (kg^{-1}). The second option is to maximise the profit per kilogramme (made tea green leaf) in which they will need a smaller total yield increase to justify the use of composites in tea production.

Increasing yields from composite plants

For the growers to achieve the necessary yield increase particularly when there is small profit kg^{-1}, the use of rootstocks that will result into greater improvement on the yields of the scions is essential. As proposed by Nyirenda (1995), this can be achieved by grafting low-yielding good quality clones on invigorating rootstocks. As not all low-yielding clones will benefit from being grafted onto the invigorating rootstocks, lack of criteria to match scions to the appropriate rootstocks is a limiting factor to this option.

Reduction of the cost of production

The profit per kilogramme (made tea or green leaf) can be maximised by reducing the cost of production and/or increasing the value by improving tea quality. This will make the use of composite plants worthwhile even with small total yield increase due to grafting. The cost of producing composite plants was three times higher than that of the conventional plants. Reducing this cost then will substantially reduce the total cost of producing composite plants and therefore growers would require small total yield increase to justify the use of composite plants. The cost of producing plants is made up of two major components namely: the cost of pruning mother bushes and the associated loss of revenue due to the loss of yield in the pruned area and the cost incurred in the actual grafting work. The cost associated with the grafting work depends on the labour productivity and the nursery success rate.

Cost of pruning mother bushes and the associated loss of revenue: the cost of pruning mother bushes together with the associated loss of revenue from the pruned area is 58% of the total cost of producing composite plants (ha^{-1}). One possibility of reducing this cost which has seen some success in Malawi, is producing composites using pluckable shoots instead of the conventional cuttings (Nyirenda and Mphangwe, 2000). This means that growers would not incur pruning cost and also the loss of revenue due to loss of yield would be equivalent to one harvest when the shoots are collected for grafting.

Improving labour productivity: due to low labour productivity, the labour cost in producing plants by grafting was about three times higher than the conventional method. Increasing labour productivity in producing composites close to the ungrafted plants would substantially reduce the total cost of producing composite plants. This can be achieved by training the nursery staff and also looking other means such as developing a grafting machine, a possibility which has shown some promising results in India.

Increasing nursery success rate: the low success rate in producing plants by grafting compared with the conventional method implies that more plants (ha^{-1}) need to be produced which means more cost. Increasing the nursery success rate of composite plants close to the ungrafted plants, again through training the nursery staff will reduce the cost of producing plants by grafting.

Reducing the costs described above would largely reduce the total cost of producing composite plants. Similarly, improving tea quality by using good quality scion clones would increase the value of the processed tea in the market and hence can fetch good prices, which means more profit per kilogramme (kg^{-1} made tea). Tea growers would therefore need small total yield increase due to grafting to make the investment worthwhile.

Figure 31 (for scion S15/10) and Figure 32 (for scion K35) suggest that the chances of getting annual yield increase which will eventually sum up to reach the total yield increase sufficient to make the use on composites in tea production viable were higher for some rootstock/scion combinations. It is useful to note that the total yield increases required to make the investment worthwhile need not necessarily be achieved in one year (although the earlier is the better). With the probabilities of achieving annual yield increases when scion clones S15/10 and K35 were grafted onto rootstocks 6/8 and SFS150 respectively, it is likely that tea growers would reach the total yield increase necessary to make the use of composites worthwhile earlier for these combinations.

PLANT SURVIVAL

Since tea is a perennial crop with an economic life of up to 100 years, assessment of the benefits should take into account this long period. Plant survival during severe drought periods is one of the key factors that need consideration when choosing planting material. In many tea growing areas drought periods resulted in loss of a substantial number of tea bushes. For example, up to 21% of the bushes (ha^{-1}) died during the 1986/87 drought in Malawi (Nyirenda and Mphangwe, 2000). Similarly, in Kenya 22 - 66% of tea bushes in some fields at Brooke Bond Kenya Limited died in the 1997/98 severe drought (Corley, 2001). Likewise, in Tanzania most of the smallholders' fields are found to have gaps, which are likely to be caused by drought. When such losses occur, tea growers would incur the extra costs of producing plants for infilling, for the infiling exercise and for maintaining the plants until they are fully established. Such additional costs have to be considered when assessing the benefits from different planting materials in tea production. For example, using the assumptions in Table 12 for the conventional method, tea growers in Malawi and Kenya (see above) would incur 8 - 22% of the initial cost of producing plants (ha^{-1}) to produce enough plants for infill the gaps caused by drought.

Any assessment of benefits therefore should take into account not only the short term benefits (e.g. yield) but also the long term benefits such as survival. In this study, although the grafted plants did not improve the yields significantly, some of the grafted plants survived the drought better than the ungrafted plants. In terms of maintaining yields and survival during the dry seasons, tea growers in areas prone to drought would therefore benefit from some of the combinations (e.g. S15/10 on 6/8 and K35 on SFS150) evaluated in this study.

CONCLUSIONS

The labour cost for producing plants by grafting has been estimated to be about three times more than that of the conventional method, but is still a very small proportion of the total cost of establishing tea. The payback period however, was the same for both methods, but this period for smallholders was shorter than the commercial companies. The payback period was in year 1 (i.e. the first season of harvesting) for the smallholders compared with year 2 or 3 (depending on the prices of made tea) for the commercial companies.

The total yield increase due to grafting necessary to make the use of composite plants in tea production worthwhile depends on the profit per kilogramme (made tea or green leaf). However, there were higher chances of getting annual yield increase which will eventually sum up to give the total yield increase necessary to make the use of composite plants worthwhile for some combinations such as S15/10 on 6/8 and K35 on SFS150.

Despite the downward trend in world tea prices, which affect the benefits to be realised from composite plants, commercially, grafting can be used to combine the best attributes of individual cultivars to improve production both in terms of quantity and quality. Lack of clearly defined criteria to identify the best rootstock/scions combinations however, limits the efficient use of composite plants in tea production.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

In many tea growing regions of the world, increasing tea production per unit area both in terms of quantity and quality remains the only viable option to compete with the decline in tea prices. This can be achieved through incorporating appropriate technologies as well as improving management practices in tea production. The use of improved planting materials is one of the possible management options which can enable the tea industry to compete with the downwards trend of tea prices, and therefore to remain in business. With this in mind, this thesis reports the results of the study on the use of composite plants in tea production as one way of producing improved planting material. The main objectives of the study were (a) to evaluate the water use and the responses to water stress of selected rootstock/scion combinations, (b) to evaluate the yield responses to drought and irrigation (c) to assess the effect of rootstocks on the composition of the harvested shoots, (d) to seek to specify criteria for matching rootstocks and scions, and (e) to specify the circumstances under which the use of composite tea plants is likely to be financially viable.

These objectives are largely met in this study and this chapter summarises the main conclusions together with its implications for the tea industry. The way forward to increase our knowledge for the efficient use of composite plants in tea production is also proposed.

WATER USE AND RESPONSES TO WATER STRESS

Evaluating the water use and the responses to water stress of composite tea plants revealed that none of the rootstocks tested had a significant effect on either the water use or the water stress as assessed by the midday xylem water potential. The choice of the scion however, influenced the response of composites to water stress. That is, the effects of a rootstock on the water availability to the scion depend on the scion clone used.

During the dry season, some composite plants survived the drought better than the ungrafted plants. Overall scion clone K35 survived the drought better than scion S15/10, which implies that the rootstocks improved the drought tolerance of clone K35 more than S15/10. Using the midday xylem water potential and visual assessment during the dry season, the ranking of the rootstocks in terms of drought tolerance would be clone PC81<6/8<SFS150.

Regression analysis to test relationship between xylem water potential and the ETa/ETpan ratio showed that a strong linear relationship exists between midday xylem water potential and ETa/ETpan ratio. The ETa/ETpan ratio decreases linearly at a rate of 0.24 $(MPa)^{-1}$, which implies that with a small change in xylem water potential, the actual transpiration rate would be affected before there is any noticeable effect on other factors (e.g. yield).

For the Ngwazi soils, actual soil water deficits between 0 and 150 mm which is equivalent up to 53% of AWC depletion had no effects on the observed midday xylem water potential.

These results are of interest particularly for small-scale tea growers who entirely rely on rainfall. Although severe drought occurs only occasionally, when this happens, these farmers lose a substantial number of tea bushes in their fields. For the sustainability of the tea industry particularly the smallholders' sector, the use of plants that would maintain yields and survival during the dry season is vital. It is likely therefore that tea growers would benefit from some of the rootstock/scion combinations tested in this study such as S15/10 on 6/8 and K35 on SFS150.

YIELD RESPONSES TO DROUGHT AND IRRIGATION

Over the period of four full years of yield recording, there were no distinct rootstock effects on the mean annual yield of the scion under all water regimes. The irrigation treatments however, significantly affected the mean annual yields. Similarly, with the exception of the first full season of harvesting (1997/98) when the mean annual yields from the scion treatments were similar, the mean annual yields from the two scions for the rest of seasons were different. As expected, the annual yields from the well watered treatments were higher than those from the unirrigated plots. For the scion treatments, with the exception of 1997/98 season, scion clone S15/10 consistently out-yielded K35 over the rest of the period of yield recording.

Evaluating the yield responses to drought showed that the two scion clones responded to the drought differently. Average potential soil water deficits up to 220 mm (range between years after field planting 130 to 290 mm) did not affect the annual yield of scion clone K35. Above 220 mm of potential SWD, the mean annual yield of this scion decreased linearly at an average rate of 6.4 kg $(ha\ mm)^{-1}$ (ranging between years 4.2 - 8.4 kg $(ha\ mm)^{-1}$). For scion clone S15/10 however, the mean annual yield was affected when the potential SWD exceed 50 mm. Above this figure, the yield of scion clone S15/10 decreased at an average rate of 5.4 kg $(ha\ mm)^{-1}$ (ranging between years 5.0 – 5.8 kg $(ha\ mm)^{-1}$).

Although the annual yields from the grafted and the ungrafted plants did not differ significantly in all water regimes, some rootstocks appeared to improved the yields of the scions, but this improvement was more in the driest plots than in the well watered treatments. For example, in the driest plots, an overall mean annual yield increase due to grafting (across rootstock treatments) of 310 kg ha^{-1} (9%) was recorded from scion clone S15/10. By contrast, in the well-watered treatments, the overall annual yield increase due to grafting was less than 1%. For scion clone K35 however, the overall annual yield increase whether irrigated or unirrigated was less than 3%.

With the exception of the graft combinations S15/10 on 6/8 and K35 on SFS150 in the unirrigated plots in which there were consistent annual yield increases due to grafting, the yield increases from all other combinations diminished with year after planting.

The above results suggest that soil water availability modifies the effects of rootstock on the yield of the scion, but this modification depends on the scion clone used. This means that the growing environment in term of water regimes or rainfall availability needs to be considered as it influences the expected benefits. Such information is important for tea growers of different capacities ranging from commercial estates who are able to irrigate (fully or partially) to smallholders who are entirely depend on rainfall. The information can help tea growers to choose the appropriate production systems to optimise profit.

COMPOSITION OF HARVESTED SHOOTS

The composition of the harvested shoots in each size category (e.g. one leaf and a bud, two leaves and a bud, and dormant shoots) and the proportions of total fresh weight that were composed of coarse and broken leaf from the grafted and the ungrafted plants were similar. Since the harvesting regime was standard, these results imply that grafting a scion clone onto a rootstock would not change the composition of the harvested shoots. The results suggest that the rootstocks did not influence the shoot growth rates of the scions.

In most of the factories in the Southern Highlands of Tanzania, the composition of harvested shoots namely: shoots of different sizes/stages, the proportions of broken and coarse leaf as well as the number of shoots per kilogramme of green leaf are commonly used to assess the green leaf quality. All these categories from both the grafted and the ungrafted plants were within the acceptable factory standards. Similarly, Kayange *et al.* (1981) and Bore (1997) found that the quality of the processed tea from the grafted plants and their respective scion clones when planted on their own roots was similar. These findings imply that good quality clones can be used as scions to increase the production of good quality tea.

As the world tea prices are characterised by a downward trend over years, for the tea industry to remain in business, it has to counter this trend of prices. The production of good quality tea would be one option, which can ensure better prices in the market. For the sustainability of the tea industry therefore, grafting to combine both quality and quantity attributes of individual clones can be used to increase tea production.

SELECTION CRITERIA

Lack of clear selection criteria to enable scientists and managers to select scions and match them to the appropriate rootstocks is the main factor limiting the efficient use of composite plants in tea production. This study intended to seek to specify selection criteria, but the fact that none of the rootstocks tested had a significant effect on the important attributes such as yield and drought tolerance of the scions made the attempt to specify criteria difficult. Likewise, lack of rootstock effects on the bush morphology as assessed by crop cover development, shoot population density, stem diameter and number of branches has limited our understanding on how the rootstocks bring about their influence on the scions which again made the effort to seek to specify criteria for matching rootstocks and scions more complex. The details and the duration required as well as the cost involved therefore, meant that it was not possible to achieve this objective in this study. Nevertheless, the study revealed that the individual clonal characteristics, which are the commonly used criteria to match rootstocks and scions on their own are not reliable criteria. These characteristics however, provide a useful guide in identifying suitable rootstocks and scions.

The growth of a composite plant is influenced by both internal and external factors. The internal factors are those related to the genetic make up of the cultivars (i.e. the rootstock and the scion) and the external are those mainly related to the growing environmental conditions (e.g. climate and day-to-day weather conditions, soils, altitude, and pests and diseases). In matching a scion to the appropriate rootstock, these factors have to be considered as they affect the expected benefits. For example, a clone that is affected by some environmental factor (s) can benefit from being grafted onto a rootstock that would improve its growth/performance under such growing environments. This view has been supported by the results from this study. For instance, there were no yield benefits when scion clone S15/10 was grafted onto the three rootstocks (i.e. SFS150, 6/8 and PC81) under well-watered conditions, but in the driest plots, although not significant, an overall annual yield increase of about 9% was achieved.

The internal and external factors play a major role in a composite plant. These factors need to be considered in defining the additional criteria for matching scions to the appropriate rootstocks to improve the expected attributes.

FINANCIAL VIABILITY

Assessing the financial viability of composite plants in tea production was important, as tea growers would not adopt the technology if it were not financially viable. The objective was met by examining the economics of using composites in tea production. The results have shown that the use of composite plants by both small and larger-scale tea producers is financially viable, but the benefits to be realised depend on the rootstock/scion combinations used as well as the market prices. This means that the decision of the tea growers to opt to use composite plants is strongly influenced by the market price and also limited by the selection criteria to identify the suitable rootstock/scion combinations.

The payback period for both small and larger-scale tea growers when plants were produced by grafting and by the conventional method was the same, but small-scale growers recovered the money invested one to two years earlier than the commercial companies. For the smallholders, the payback period for both methods of producing plants was in year 1 (i.e. the first season of harvesting). For the commercial companies, depending on the market price of the processed tea, this period was in year 2 or 3.

The additional cost of producing plants when the larger-scale tea growers opt to use composites rather than the conventional plants was estimated to be US $ 100 ha^{-1}. The corresponding figure for the small-scale growers was US $ 47 ha^{-1}. The total yield increase necessary to cover this extra cost depends on the production cost (i.e. US $ kg^{-1} of made tea or green leaf). The fact that the production cost varies with company and maybe with the individual smallholder, the total yield increase necessary to cover the additional cost of producing plants by grafting will therefore be different between growers. Nevertheless, knowing their production cost, tea growers would be able to determine the profit per kilogramme of made tea or green leaf and hence the total yield increase they need to cover the extra cost of producing plants when they opt to use composites.

Although the statistical analysis showed no significant yield difference between the grafted and the ungrafted plants, the probability of achieving a yield increase sufficient to make the investment worthwhile was higher for some rootstock/scion combinations such as S15/10 on 6/8 and K35 on SFS150. The overall benefits from these combinations however, depend on the production cost and/or the tea prices (US $ kg^{-1} made tea of green leaf).

In this study, despite the fact that the rootstocks tested had no significant effects on the attributes such as yield and drought tolerance of the scions, the work highlighted the possible potential of composite plants in tea production. The lack of significant rootstock effects might have been caused by the small number of replicates in the experiment due to poor success rate obtained in the nursery. Increasing the number of replicates would have probably made it possible to pick up smaller rootstock effects. However, Pearce (1976), suggested that replication has to increase fourfold to halve the standard error. This means that the land area has to increase four times to accommodate the experiment. For a line source experiment, such an area can be difficult to maintain uniformly and is also costly as it requires a larger pumping unit. In this study however, four replicates would have been possible with the land area and the irrigation equipment available if there had been enough plants.

A WAY FORWARD

Currently, composite tea plants are not used in a commercial scale in Tanzania. Apart from the area of the experiment under this study and few small plots attempted by some commercial companies, to date the area under composite tea plants in Tanzania can be considered to be zero. By comparison, in Kenya, the area under composite tea plants was estimated to be 300 ha (Corley, 2000). Similarly, in Central Africa, composites are estimated to occupy about 100 ha (Martin, 1998). Likewise, in South India, composite plants have been commonly used for commercial tea production. In fact South India probably has the largest area under composite tea plants in the world.

Although there are a number of key areas such as selection criteria and the technical difficulties in producing plants that need to be addressed for efficient use of composites, the above comparison suggests that composite plants can as well be used in Tanzania. The fact that some commercial companies have attempted to produce composite plants meant that they are aware of the possible potential that composites can play to increase tea production. The results of this study described above seem to support this idea.

The production of composite plants is a limiting factor to the adoption of composites by the tea industry. Tea growers face technical difficulties in producing the plants (Nyirenda, 1995). Apart from the possible benefits described above therefore, the tea growers would be familiar with the techniques if composite plants are introduced at this stage. The experience of grafting work in Malawi has shown that success rate as low as 60% was achieved in the early attempts of grafting (Scarborough, 1981), but recently success rates up to 95% are achieved in the commercial nurseries (Nyirenda and Mphangwe, 2000). This suggests that for successful production of composite plants skilled grafters are required. Introduction of composite plants would allow tea growers to acquire the skills and techniques required to produce the plants. By the time most of the constraints to the efficient use of composites are resolved (although it is a slow process), nursery success rates comparable to those of the conventional method of producing planting materials should be achieved.

Future research

The most important task at present is to address the key areas that have been found to limit the efficient use of composite plants in tea production. Lack of clear selection criteria to enable scientists and managers to select scions and match them to the appropriate rootstocks and the technical difficulties in producing composite plants are the main factors limiting the adoption of composite plants by the tea industry.

Selection criteria

In general, the primary objectives of most of the previous experimental work on composite plants, not only on tea, but also on other crops were to increase attributes such as yield and/or quality and drought resistance. Researchers have concentrated on achieving these objectives, while very little emphasis seems to have been made to explain the underlying mechanisms. This lack of knowledge on how the rootstocks bring about their influence on the scions means that researchers have not been able to define criteria for selecting scions and matching them to the appropriate rootstocks. For the efficient use of composite plants in tea production, criteria are required to match the scions to the appropriate rootstocks to improve the expected attributes.

Production of composite plants

The technical difficulty in production of composites is another limiting factor to the adoption of composite plants by the tea industry. One possibility, which has seen some success in India, would be developing and testing a grafting machine to improve labour productivity.

The research undertaken in Tanzania provides information of great value on the potential of composite plants in tea production, particularly to the Tanzanian tea industry in which composite plants are currently not used in a commercial scale. The work proves that the use of composite plants is technically feasible, but their use maybe limited to specific areas and perhaps to unirrigated tea production. The study has also increased our understanding of the possible mechanisms controlling the behaviour of composite plant.

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APPENDICES

APPENDIX A: A DUMMY STATISTICAL ANLYSIS OF THE EXPERIMENT

Appendix A.1: *Genstat programme*

```
          Genstat 5 Release 4.1  (PC/Windows 95)

Copyright   1997,Lawes   Agricultural   Trust   (Rothamsted
Experimental Station)
```

```
          Genstat 5 Third Edition (for Windows)
          Genstat 5 Procedure Library Release PL10
```

```
DELETE[redefine=yes]
Blocks,Irrigation,Rootstock,Scion,Distance
   FACTOR [modify=yes;nvalues=120;levels=!(1,2)] Blocks
   READ Blocks; frepresentation=ordinal

    Identifier    Values   Missing    Levels
        Blocks       120         0         2
 FACTOR
[modify=yes;nvalues=120;levels=6;labels=!t('I0','I1','I2',\
'I3','I4','I5')] Irrigation
READ Irrigation; frepresentation=ordinal

    Identifier    Values   Missing    Levels
      Irrigation     120         0         6
FACTOR
[modify=yes;nvalues=120;levels=5;labels=!t('6/8','K35',\
'PC81','S15/10','SFS150')] Rootstock
  READ Rootstock; frepresentation=ordinal

    Identifier    Values   Missing    Levels
      Rootstock      120         0         5
FACTOR
[modify=yes;nvalues=120;levels=2;labels=!t('K35','S15/10')]
Scion
  READ Scion; frepresentation=ordinal

    Identifier    Values   Missing    Levels
         Scion       120         0         2
VARIATE [nvalues=120] Distance
  READ Distance
```

Identifier	Minimum	Mean	Maximum	Values	Missing
Distance	3.00	24.00	45.00	120	0

```
"General Analysis of Variance."
BLOCK Blocks/((Rootstock.Scion)*Irrigation)
TREATMENTS Rootstock*Scion*Irrigation
COVARIATE Distance
ANOVA       [PRINT=aovtable,information,mean,%cv,covariate;
FACT=3; FPROB=yes; PSE=diff,lsd,means]
```

Appendix A.2: Analysis of variance (adjusted for covariate)

Covariate: Distance

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum					
Covariate	1				
Blocks.Irrigati stratum					
Irrigati	5				
Covariate	1				
Residual	4				
Blocks.Rootstoc.Scion stratum					
Rootstoc	4				
Scion	1				
Rootstoc.Scion	4				
Residual	9				
Blocks.Rootstoc.Scion.Irrigati stratum					
Rootstoc.Irrigati	20				
Scion.Irrigati	5				
Rootstoc.Scion.Irrigati	20				
Residual	45				
Total	119				

Appendix A.3: *Covariate regressions*

Covariate	coefficient	s.e.
Blocks stratum		
Distance		
Blocks.Irrigati stratum		
Distance		
Combined estimates		
Distance		

APPENDIX B: SUMMARY OF YIELD DATA

***Table B.1: Tippings**: effects of rootstock on the dry yield of tippings (i.e. the first five months of harvesting, January to May 1997) from scion clones S15/10 and K35 grafted onto rootstocks PC81, SFS150 and 6/8. 'Opps' refers to the rootstock/scion combinations S15/10 on K35 and vice versa. 'Control' refers to the ungrafted scion clones. The plants were planted in the field in February 1996. The experiment was uniformly irrigated.*

	Yield of dried tea (kg ha^{-1}) **Rootstock**					
Scion	Control	Opps	SFS150	6/8	PC81	**Mean**
S15/10	250	400	380	450	530	**400**
K35	310	300	410	350	360	**350**
Mean	**280**	**350**	**390**	**400**	**440**	**370**

s.e.d. between: scion treatments = 20 (df = 9);
rootstock treatments = 32 (df = 9);
rootstock x scion treatments = 46 (df = 9);
coefficient of variation = 14.5%

***Table B.2: 1997/98 season**: effects of rootstock on the annual yield (1 June 1997 to 31 May 1998) of dried tea from scion clones S15/10 and K35 grafted onto rootstocks PC81, 6/8 and SFS150. 'Opps' refers to the rootstock/scion combinations S15/10 on K35 and vice versa. "Control" refers to the ungrafted scions. The experiment was uniformly irrigated.*

	Yield of dried tea (kg ha^{-1}) **Rootstock**					
Scion	Control	Opps	SFS150	6/8	PC81	**Mean**
S15/10	2,480	3,220	3,040	3,270	3,540	**3,110**
K35	2,780	2,850	3,080	3,070	2,810	**2,920**
Mean	**2,630**	**3,030**	**3,060**	**3,170**	**3,170**	**3,010**

N.B. None of the treatments had a significant effect on the mean annual yield.

***Table B.3: 1998/99 season**: effects of maximum potential soil water deficit on the mean annual yield of dried tea (1 June 1998 to 31 May 1999) of scion clones S15/10 and K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scion clones. The plants were planted in the field in February 1996.*

		Yield of dried tea (kg ha^{-1})						
		Dry ←	Irrigation treatments			→	**Wet**	
		I_0	I_1	I_2	I_3	I_4	I_5	
Maximum SWD (mm)		400	380	270	130	60	60	
Irrigation (mm)		490	510	610	760	860	890	
Scion	**Rootstock**							**Mean**
S15/10	Control	3,250	3,710	4,610	4,900	4,900	5,760	**4,520**
	PC81	3,580	3,930	5,020	5,610	5,450	5,810	**4,900**
	6/8	4,050	4,230	4,820	5,320	5,470	5,570	**4,910**
	SFS150	3,990	3,860	4,640	4,720	4,990	5,600	**4,630**
	K35	3,790	4,160	5,120	5,720	5,910	6,280	**5,160**
Mean		**3,730**	**3,980**	**4,840**	**5,250**	**5,340**	**5,800**	**4,830**
K35	Control	3,170	3,260	4,200	4,270	4,130	4,430	**3,910**
	PC81	3,020	3,290	3,810	4,240	4,170	4,530	**3,840**
	6/8	3,280	3,740	4,200	4,670	4,700	4,660	**4,210**
	SFS150	3,370	3,440	4,130	4,420	4,110	4,480	**3,990**
	S15/10	2,750	3,490	4,360	4,370	4,560	4,880	**4,070**
Mean		**3,120**	**3,440**	**4,140**	**4,390**	**4,330**	**4,600**	**4,000**
Grand mean		**3,420**	**3,710**	**4,490**	**4,820**	**4,840**	**5,200**	**4,420**

s.e.d. between:
scion treatment = 131 (df = 9);
irrigation treatments = 74 (df = 4);
scion x irrigation treatments = 172 (df = 45);
coefficient of variation = 7.2%.

***Table B.4: 1999/00 season**: effects of maximum potential soil water deficit on the mean annual yield of dried tea (1 June 1999 to 31 May 2000) of scion clones S15/10 and K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scion clones. The plants were planted in the field in February 1996.*

		Yield of dried tea (kg ha^{-1})						
		Dry ←	Irrigation treatments			→	**Wet**	
		I_0	I_1	I_2	I_3	I_4	I_5	
Maximum SWD (mm)		470	450	240	100	60	50	
Irrigation (mm)		340	360	570	730	810	860	
Scion	**Rootstock**							**Mean**
S15/10	Control	3,380	4,100	5,270	5,520	5,570	6,490	**5,060**
	PC81	3,760	4,350	5,800	6,230	6,250	6,550	**5,490**
	6/8	4,490	4,650	5,900	6,060	6,280	6,250	**5,610**
	SFS150	3,440	4,180	5,120	5,340	5,400	6,340	**4,970**
	K35	3,670	4,400	5,020	5,970	5,930	7,160	**5,360**
Mean		**3,750**	**4,340**	**5,420**	**5,820**	**5,890**	**6,560**	**5,300**
K35	Control	3,410	3,920	5,090	5,200	5,070	5,330	**4,670**
	PC81	2,790	3,240	4,220	4,380	4,560	5,180	**4,069**
	6/8	3,600	4,710	5,560	5,280	5,460	5,760	**5,060**
	SFS150	3,920	4,220	4,970	5,340	5,190	5,510	**4,860**
	S15/10	2,900	4,000	5,030	5,180	4,970	5,270	**4,560**
Mean		**3,320**	**4,020**	**4,970**	**5,080**	**5,050**	**5,410**	**4,640**
Grand mean		**3,540**	**4,180**	**5,200**	**5,450**	**5,470**	**5,980**	**4,970**

s.e.d. between: scion treatments = 191 (df = 9);
irrigation treatments = 144 (df = 4);
scion x irrigation treatments = 251 (df = 45);
coefficient of variation = 5.8%.

***Table B.5: 2000/01 season**: effects of maximum potential soil water deficit on the mean annual yields of dried tea (1 June 2000 to 31 May 2001) of scion clones S15/10 and K35 grafted onto rootstocks PC81, 6/8 and SFS150. The scions were also grafted on each other (i.e. S15/10 on K35 and vice versa). Control refers to the ungrafted scion clones. The plants were planted in the field in February 1996.*

		Yield of dried tea (kg ha^{-1})						
		Dry ←	Irrigation treatments			→	**Wet**	
		I_0	I_1	I_2	I_3	I_4	I_5	
Maximum SWD (mm)		490	470	290	150	80	60	
Irrigation (mm)		290	310	540	710	800	870	
Scion	**Rootstock**							**Mean**
S15/10	Control	4,120	4,740	6,220	6,600	7,020	7,020	**5,950**
	PC81	3,790	4,660	6,150	6,800	6,760	6,600	**5,790**
	6/8	4,430	4,870	5,790	6,230	6,250	6,310	**5,650**
	SFS150	3,990	4,490	5,570	6,030	6,220	6,900	**5,530**
	K35	3,780	4,500	5,820	6,640	6,760	6,950	**5,740**
Mean		**4,020**	**4,650**	**5,910**	**6,460**	**6,600**	**6,760**	**5,730**
K35	Control	3,650	4,690	5,330	5,710	5,700	5,890	**5,160**
	PC81	3,190	3,860	5,280	5,830	5,380	5,720	**4,880**
	6/8	3,760	4,690	5,390	5,610	5,820	5,870	**5,190**
	SFS150	4,110	4,620	5,640	5,920	5,520	5,720	**5,260**
	S15/10	3,640	5,080	5,720	5,860	6,040	6,120	**5,410**
Mean		**3,670**	**4,590**	**5,470**	**5,790**	**5,690**	**5,870**	**5,180**
Grand mean		**3,840**	**4,620**	**5,690**	**6,120**	**6,140**	**6,310**	**5,450**

s.e.d. between: scion treatments = 220 (df = 9);
irrigation treatments = 124 (df = 4);
scion x irrigation treatments = 268 (df = 45);
coefficient of variation = 6.3%.