SEASON EFFECTS ON THE POTENTIAL BIOMASS AND SUCROSE ACCUMULATION OF SOME COMMERCIAL CULTIVARS OF SUGARCANE

by

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DECLARATIONS

The work described in this thesis was conducted under the supervision of Professor PL Greenfield in the Faculty of Science and Agriculture, University of KwaZulu-Natal, Piertermaritzburg.

As the candidate's Supervisor I agree/do not agree to submission of this dissertation/thesis.

Signed:…….. Date……

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ABSTRACT

An experiment was conducted at Pongola (27°24´S, 31°25´E; 308m altitude) in South Africa to study the effects of season on growth and potential biomass and sucrose yields on nine commercial sugarcane cultivars. The treatments that were the focus in this study consisted of the cultivars NCo376, N25 and N26 ratooned in March, April, May, August and December. The crops were well fertilized and kept free of weeds and diseases. Irrigation applications were scheduled with a computer programme to keep the crops free of stress at all times. Shoot populations were counted regularly to study shoot density dynamics. Leaf appearance rates, sizes, numbers and senescence were measured to study the development of green leaf area. Green foliage, dead trash and stalk mass were measured at 4, 8, 10, 11 and 12 months in each of the starting times and also at 13 months in the March, April and May ratoon crops. The fibre, sucrose and non-sucrose content of stalks were determined on these harvesting occasions. Yields were calculated in terms of individual shoots and area (m^{-2}). The fraction of PAR intercepted by the developing canopies was measured until full canopy and daily intercepted solar radiation was interpolated for the entire crop. An automated meteorological station adjacent to the experiment site provided daily weather data.

Shoot densities were described by thermal time, however, average peak shoot densities were lowest in the May ratoon (31.8 m^{-2}) and highest in the December ratoon (48.7 m^{-2}). Shoot senescence was most rapid in August and December ratoons. At the final harvest shoot densities were highest in the March, April and May ratoon (14.8 to 14.2 m^{-2}) crops. NCo376 (16.4 m^{-2}) and N25 (13.6 m^{-2}) had higher final shoot densities than N26 (10.5 m^{-2}). Leaf appearance rate was also well described by thermal time, however the first twelve leaves took longer to appear in crops started in December i.e. the first phyllochron was longer (109.5°C d) than in crops started at other times (80.4 to 94.5°C d). Leaves produced during the early stages of December and August ratoon crops were larger (e.g leaf number 13 of N26 was 443 to 378 cm^2) than in other crops. April and May ratoon crops produced much smaller leaves (e.g leaf number 9 of N26 was 170 to 105 cm^2). Leaf senescence was slower in April and May ratoon crops (0.36 to 0.46 leaves per 100°C d) than in March (0.51 to 0.59 leaves per 100°C d) or August and December ratoon crops (0.60 to 0.68 leaves per 100°C d). December ratoon crops produced very high green leaf area indexes (LAI) (>7.0) at the age of four months; all

other crops had lower LAI (3.3 to 6.0) and most peaked later (8 to 11 months of age). The LAI of N25 peaked at the age of 8 months while NCo376 and N26 peaked when 10 to 11 months old. Seasonal fraction of solar radiation intercepted was high in the March ratoon crops (0.84) and declined to 0.63 in the May ratoon crops and was highest in the December ratoon crop (0.88). N26 intercepted lower fractions of PAR than NCo376 and N25, particularly in the May and August ratoon crops.

Biomass accumulation, although initially slow, tended to be linear in the March, April and May ratoon crops in relation to intercepted radiation. In August and particularly in the December ratoons biomass accumulation was initially rapid, and RUEs were high (2.65 g MJ^{-1} at 114 days in the December ratoon crops). However, biomass accumulation slowed when these December ratoon crops experienced winter. Low growth rates after winter, as well as low shoot densities resulted in December ratoon crops having produced significantly lower above-ground biomass yields (4 886 g m^{-2} at the age of 12 months) than March, April and May ratoon crops (6 760 to 5 715 gm^{-2} at the age of 12 months). The December ratoon crops responded poorly to the better growing conditions in spring and second summer and accumulated little biomass after winter. N26 shoots grew rapidly during the first 6-8 months of the December ratoon crop and it yielded better than NCo376 and N25 at harvesting (biomass yields were 5.8 and 13.3% higher at the age of 12 months, respectively). April ratoons produced significantly higher biomass yields (6 760 g m^{-2}) than March, August and December ratoons. May ratoon crops produced the highest cane fresh mass yields (18 151 g m^{-2}) and April, May and August ratoons produced significantly higher sucrose yields than March and December ratoons. The highest sucrose yield was produced by the April ratoon crop of N26 (2 385 g m^{-2}). On average, across the five ratoon dates, NCo376, N25 and N26 produced similar sucrose yields (1 902 to 1 959 g m^{-2}). Foliage production was severely limited during winter while sucrose accumulation was less affected by the low temperatures, resulting in accumulation of sucrose in the top sections of the culm.

Low temperatures slowed the development of canopies in March, April and May ratoon crops, but these crops were able to recover their growth rates and produced high biomass and sucrose yields at the age of 12 months. The December ratoons experienced low winter temperatures (<12°C) when they had already accumulated relatively high yields and became moribund during winter. They were unable to

accumulate any significant amounts of biomass during final four months before the final harvest at the age of 12 months. NCo376, N25 and N26 all yielded poorly in the December ratoon crop. However, there are cultivars that appear to be less sensitive to the low winters and are able to yield relatively well when they are ratooned in December. Sucrose yields of March, April and May ratoons were increased substantially (10.6 to 22.7%) by harvesting at the age of 13 months rather than at the age of 12 months.

The poor growth of December ratoon crops after winter is possibly due to the recently revealed feedback signaling by high sugar levels induced by low temperatures on photosynthesis. The incorporation of the effects of low temperature and the feedback signaling with the objective of better simulating yields of December ratoons is a proposed study at the South African Sugarcane Research Institute. Annual mean sucrose yields of NCo376, N25 and N26 crops were estimated to be 17% higher in March than in December ratoons. The suggested short term remedy therefore of the poor December yields is to shift milling seasons to include March and exclude December harvested crops in the northern irrigated regions. March crops grow vigorously during the months close to harvesting and therefore have lower levels of sucrose content which can be corrected with chemical ripeners.

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LIST OF ABBREVIATIONS AND DEFINITION OF TERMS

Annual	Crop age at or close to12 months
Base temperature	The temperature at which growth (or a process) stops
Biomass	Dry mass after water has been removed in a crop
Brix	The water soluble component of sugarcane juice
Extinction coefficient (*k*)	A coefficient describing the behaviour of light passing through the green leaf canopy
Fibre	The water insoluble portion of leaves, roots and stalks
Germination	Bud break
L	Green leaf area, collective area of individual leaves
LAI	Leaf area index, the total green leaf area per unit land surface
PAR	Photosynthetically active radiation, falling in the waveband of 400-700*nm*
Phyllochrons	A temperature related time laps between the emergence of sequential leaves on a shoot
Radiation use efficiency	The efficiency of biomass production relative to the cumulative intercepted solar radiation
Ratoon	A crop that propagates from the subterranean buds left after harvesting the previous crop
Shoots	Plant units in sugarcane crops that do not distinguish between primary and secondary shoots produced by tillering
Solar radiation	Total spectrum of sunlight
Thermal time (°C d)	The cumulative heat units above the base temperature of a growth process
Tillering	The process by which shoots are produced from the buds on existing shoots

CHAPTER 1

INTRODUCTION

There were substantial gains in sugar yields between 1950 and 1970 in the South African sugar industry from the introduction of new cultivars together with improved husbandry practices. However, sucrose yields have remained relatively unchanged over the subsequent three decades (Watt, 2002), despite the large number of cultivars that have been released to farmers during this period. The plateau in sugar yields has been ascribed to a narrow genetic base in the germplasm used in traditional breeding programmes (Watt, 2002). In growth simulation models, like CANEGRO (Inman-Bamber, 1991b), various growth processes are integrated so that yields can be predicted under a wide range of conditions. Further advances in the accuracy of model predictions can be made by identifying the heritable morphological and physiological parameters, also known as genetic coefficients that characterise different cultivars. Such genetic coefficients can be of value to both modelling crop growth of specific cultivars, and if heritable, could assist in targeting new cultivars in breeding and selection programmes.

Breeding and selection programmes of sugarcane are based on the knowledge, and expectation, that cultivars (genotypes) respond differently to environmental factors (GXE interactions). While a considerable amount of crop physiology has been incorporated into sugarcane crop models like CANEGRO (Inman-Bamber, 1999b) the emphasis is on linking genotypes to phenotypes through modelling. Sugarcane genotype x environment studies are needed to test and build on the existing knowledge that will improve the prediction capabilities of crop model. The CANEGRO model is based mostly on studies done on the cultivar NCo376. The present study was initiated to discover how season influences growth of a range of current commercial cultivars. Because of the large amount of data collected this study focussed on the three cultivars, NCo376, N25 and N26 that were grown in each of the five ratoon months, March, April, May, August and December.

Plant crops of sugarcane are established from vegetative stalk (culm) pieces that have a series of nodes and internodes. The nodes have buds that germinate[1] and develop into primary shoots. Each primary shoot develops leaves and a stalk that has a series of its

[1] The term germinate is used within the sugar industry to reflect bud break. It is used as such throughout the document

own nodes and internodes. The first few nodes are below the soil surface and are the sites of tillering that is typical of grass species. At the time of harvesting, the subterranean buds left on the stubble of the previous crop are released from the hormonal control exerted by the stalk apex, known as apical dominance. This break from apical dominance induces the buds to germinate, given the correct conditions to do so. Germination is favoured by moist, warm conditions and is therefore temperature dependent. These “stubble-buds” within a given area do not all germinate simultaneously. Some “stubble-buds” germinate quickly and have developed into substantial shoots with their own buds developing into secondary shoots, by the time other “stubble-buds” are only starting to break dormancy. The germination process may therefore be protracted, taking more than 40 days in plant crops (Bell & Garside, 2005). Collectively the primary shoots and tillers are the units that form the crop and are here referred to as shoots, rather than tillers. The process of higher order shoot production is referred to as tillering. Shoots are the leaf bearing components of the sugarcane canopy. A description of the rates at which they develop can provide information that is essential in developing an understanding of the mechanisms of canopy formation related to season, radiation capture and finally on biomass production. A sugarcane canopy is comprised of a mixture of primary shoots and secondary shoots that have alternately arranged leaves on a single culm or stalk. The prolific production of shoots over time results in competition for radiation, water and nutrients that leads to death of a large portion of shoots (Inman-Bamber, 1994b). The maximum shoot density of ratoon crops was shown to occur at 500ºC d using a base temperature of 16°C for NCo376 (Inman-Bamber, 1994b). The ensuing death of shoots was attributed to a radiation threshold level (less than 30% of incident PAR) reaching the lowest level of green leaves in the canopy (Inman-Bamber, 1994b). Singels, Smit, Redshaw & Donaldson (2005b) concluded that peak shoot density occurred at 600ºC d (base 16°C) in both plant and ratoon crops. The death of shoots is initially rapid and then much slower as stable numbers of living shoots are reached after 1200ºC d (Inman-Bamber, 1994b). Five phenological phases of shoot development have been defined by Bezuidenhout (2000) namely: 1) pre-germination

2) pre-emergence
3) primary shoot emergence
4) secondary shoot emergence and
5) shoot senescence.

The time from the start of the crop to the emergence of the first shoots encompasses the phases 1 and 2 described by Bezuidenhout (2000) and are combined in this thesis into a phase called shoot pre-emergence. This is followed by the emergence of a large number of shoots defined as shoot emergence or phase 2. During phase 2 (shoot emergence) there are two distinct rates at which shoots emerge and these are described as two sub-phases according to rate of shoot development. The first sub-phase is characterised by profuse tillering and the second by a decline in tillering rate and is associated with more rapid stalk elongation as the light environment changes due to competition. Phase 3 describes the senescence shoots. Bezuidenhout (2000) proposed that the completion of "stubble-bud" germination, which produces primary shoots, is marked by a decline in rate of shoot development. This change in rate of shoot development signals the beginning of a phase during which only secondary shoots appear (Bezuidenhout, 2000) which has lead to the description of two sub-phases in phase 2. Shoot development is principally driven by temperature and the amount of radiation penetrating to the lower levels of a canopy in crops that are well supplied with nutrients and water (Inman-Bamber, 1994b; Zhou, Singels & Savage, 2003).

Sugarcane leaves are formed at the stalk apex and consist of a lamina and a sheath. The sheath is attached to a stalk at a node and the segment below it is called an internode. The leaf and its associated node and internode are collectively referred to as a phytomere. Such phytomeres collectively constitute the aerial part of a sugarcane plant. Leaves are arranged in an alternate pattern forming two ranks along the length of the stalk. The laminas are strap-shaped with lengths of the largest leaves often exceeding 1.0 m while the width is usually less than 50 mm. However, the first leaves on a shoot are initially very small and may consist largely of a sheath and a very small blade. The first leaves are associated with small compressed internodes that are below the soil surface. Although sheaths are capable of photosynthesis, the leaf laminas of a fully canopied crop intercept practically all the photosynthetically active radiant flux and produce the photosynthate that drives the growth processes of sugarcane. The size of laminas and rate at which leaves are produced together with the rate at which older leaves die, determine the dynamics of green leaf area of individual shoots over time. The total green leaf area per unit land surface constitutes one unit of the green leaf area index (LAI). This green LAI determines the capacity of the crop to intercept radiation and as such determines the size of the source of photosynthate.

Leaf production was closely associated with temperature (Inman-Bamber 1994b). The thermal time between the appearances of two successive leaves is termed a phyllochron (Gallagher, 1979). The phyllochron can be calculated as the reciprocal of the slope from regressing leaf numbers with thermal time. Inman-Bamber (1994b) determined that the base temperature for leaf development of South African cultivars was 10°C. The rate at which leaves 1 to 14 were produced was quicker than later emerging leaves, thus Inman-Bamber (1994b) differentiated early leaf production rate from later leaf production by two linear equations that described two phyllochrons. It was shown that the first of the two phyllochrons for the cultivars NCo376 and N12 were 109 and 118°C d, respectively (Inman-Bamber, 1994b). The area of fully developed leaves (final leaf size) increased up to about leaf 14 after which leaf size changed little on primary shoots (Inman-Bamber, 1994b). Little is known of how shoot density and leaf development relate to canopy development in other South African cultivars. In particular, little is known about the effect that seasonal starting time of crops has on leaf development.

Sunlight, radiated as energy-packed photons, is intercepted by plants and the energy thus captured is used in the production of carbohydrates through the reduction of CO_2 in the process of photosynthesis. However, only approximately 50% of solar radiation drives the photosynthetic process and this spectrum of the radiation waveband is known as photosynthetically active radiation (PAR) (Spitters, Toussaint & Goudriaan, 1986). The photosynthetically active spectrum of radiation falls between the wavelengths of 400 and 700 nm but photosynthesis is mostly driven by specific wavelengths within this band. Alexander and Biddulph (1974) found that generally maximum photosynthesis occurred in the blue (480 nm) and in red (620-640 and 670 nm) spectra. Besides these peak activity spectra, there may be substantial activity at other wavelengths within the visible spectrum. The way radiation diminishes as it passes through a leaf canopy is characterised by a radiation extinction coefficient (*k*). The extinction coefficient is related to the height of a crop, size and shape of leaves but mostly to leaf angle and their inclination to the sun (Hay & Walker, 1989). Using an analogue of Beers' Law, (Monsi & Saeki, 1953 (cited in Purcell, 2000) described the fraction of solar radiation intercepted by a canopy as: $Li = [1\text{-}e^{-(k \times LAI)}]$. Maddonni & Otegui (1996) showed differences in *k* existed between maize hybrids that had different leaf angles and leaf areas. Rostron (1974b) showed very similar patterns of LAI development and radiation interception for the cultivars NCo376 and CB 36/14 despite their very marked differences in leaf width

and leaf angles. The attenuation of radiation as it passes through a canopy determines how effectively radiation can be distributed to lower leaves in a canopy, thus a canopy with a low *k* value is less likely to reach saturated levels of photosynthesis in the top layers of leaves (Hay & Walker, 1989). Factors that govern the development of the canopy will govern the amount of radiation intercepted. Green leaf area is a function of number of shoots, leaf sizes, number of and rates at which leaves are produced on a shoot and longevity of the leaves before senescing. The fraction of radiation intercepted by the crop is determined by the green leaf area of a plant and governs biomass production. Canopy development is strongly influenced by temperature and thermal time has often been used to predict its development (Inman-Bamber, 1994b; Singels & Donaldson, 2000).

Leaf senescence in sugarcane has been observed to start when seven leaves have appeared on a shoot (Robertson, Bonnett, Hughes, Muchow & Campbell, 1998). The senescence of these first leaves is the initiation of the dead component of trash produced by green harvested crops. In crops free of nutrient and water stress, leaf senescence was a function of leaf appearance rate (Inman-Bamber, 1994b; Robertson, Bonnett, Hughes, Muchow & Campbell, 1998). For every new fully-expanded leaf that was formed 0.91 leaves senesced. The oldest leaves die as new leaves are formed and the sequential nature of senescence suggests that new leaves and older leaves compete for solar radiation, mineral nutrients and assimilate (Hay & Walker, 1998). As shoot densities increase the competition between shoots for solar radiation triggers shoot senescence. Inman-Bamber (1994b) showed that when 70% of PAR was intercepted, shoots started dying and thereafter shoot density was largely associated with thermal time. Peak shoot densities were reached after 500°C d. Maximum shoot densities of 72.0 and 74.4 shoots m^{-2} were produced by NCo376 and N12, respectively but only 14.6 and 16.5 shoots m^{-2} survived to harvesting at 12 months of age Inman-Bamber (1994b).

The non-surviving shoots together with dead leaves of surviving shoots form the dead component of trash in green harvested crops. A trash blanket is composed of several layers. The lower layer consists of decomposing dead shoots that are shaded out during crop development, and dead leaves that are sloughed from older stalks. This is overlaid by a layer composed of dead leaves and green plant material which are parted from the

stalks when the crop is harvested. The green trash is composed of green leaves with an enclosed short immature section of the culm. Plant nutrients are continuously translocated from attached dying tissue into vigorously growing parts, and therefore the layer of top green trash contains most of the nutrients that can be recycled into the soil when the trash decomposes post harvest (van den Berg *et al*., 2006). The amounts of dead trash and green trash and their rates of decomposition determine how nutrients and organic matter are recycled to the soil. Sugarcane yields are traditionally reported in terms of cane and sucrose mass while amounts of trash are seldom reported. Furthermore, studies rarely include different cultivar types or consider the effect that season (i.e. the start and harvest dates) may have on all the components of biomass and the nutrients that may be recycled.

Advances in technology addressing ethanol production from lignocelluloses will enhance the value of trash. Alternatively, trash can be left in the field to decompose and release nutrients to the soil. This source of nutrients needs to be considered in determining the appropriate fertilization programme for maximizing productivity. Potential trash is defined as the total foliage that can be removed from stalks during harvesting and includes shoots that have died during the development of the crop. In practice some leaf material clings to the stalk after harvest and therefore not all potential trash remains in the field. Green foliage is composed of all green leaves, including partially necrotic leaves with more than 50% green area and their associated sheaths. Dead trash is all dead leaves and shoots that have died during the development of the crop. The demand for sugarcane trash as a means of reducing fertiliser inputs by recycling nutrients and improving soil health could be challenged in future by the demand for lignocelluloses as a feedstock for ethanol production. Large quantities of trash may also have deleterious effects on crop growth, and ameliorative steps may be needed to avoid this.

Productivity of cultivars at different locations can be compared on the basis of their efficiency of producing plant biomass in relation to intercepted radiation, known as radiation use efficiency (RUE) (Sinclair & Muchow, 1999). It is important to determine the limitations imposed by seasonal changes, in particular the seasonal patterns of solar radiation together with the effects of temperature on the growth of crops that start at different times in the year. Radiation and temperature set the limits of yield that can be achieved by healthy crops, free of water and nutrient stresses, and are therefore defined

as potential yields (Moore, 2005) in this study. Many studies on the productivity of sugarcane crops, free of the afore-mentioned stresses have focussed on one or two seasonal starting times with one or two cultivars (Muchow, Spillman, Wood & Thomas, 1994; Muchow, Robertson, Wood & Keating, 1997b; Robertson, Wood & Muchow, 1996; Rostron 1974b; Thompson, 1988). In a previous study of the effects of season on biomass production the fraction of trash was assumed to be a constant fraction of biomass (Thompson,1978). This notion was dispelled by Singels and Inman-Bamber (2002) when they showed that cooler temperatures favoured partitioning of dry matter away from leaves to stalks. In a growth study by Thompson (1991) the biomass yield of the cultivar N14 varied according to the time of harvest. Biomass yields of the April, August and October crops were 57, 72.7 and 62.9 tons ha^{-1} at the age of 12 months, respectively. There was good evidence that the fraction of biomass allocated to stalks was different for crops started at different times of the year (Thompson, 1991). Growth experiments showed that crops of NCo376 started in September at Mount Edgecombe produced higher yields at the age of 12 months than crops that started growth in January (Rostron, 1974b). Inman-Bamber (1994a, b) showed that crops started in August and October intercepted substantially more radiation than April ratoon crops at 12 months of age which could explain the higher yields of the August and October started crops in the Thompson (1991) data. However, crops planted in December have been shown to intercept lower fractions of radiation (see above) than crops planted in January and March (Inman-Bamber, 2000). This was ascribed to the December crop not being able to recover from the inability to use all the radiation when it was germination and developing a canopy during the peak solar radiation period. Annual crops ratooned in summer (August and December ratoons in this thesis) however, intercepted more incident solar radiation than those harvested in winter (May ratoon in this thesis) (Inman-Bamber, 2000). This was because winter ratoon crops took 2.5 times longer to reach full canopy than the summer ratoons. Severe lodging was thought to be the reason for poor yields in a December ratoon crop (Rostron, 1974b). Thompson (1988) attributed the lower productivity of aging crops to their greater demand on photosynthate for respiration as was demonstrated by Glover (1972). As sugarcane crops age specific leaf nitrogen (SLN) levels decrease below levels required for optimum rates of photosynthesis. In a review of SLN on the growth of sugarcane Van Heerden, Donaldson, Watt & Singels (2010) concluded that SLN may be a cause of slow growth in aging sugarcane crops.

In tropical Australia, crops harvested in late summer suffer yield losses due low incident radiation under cloudy conditions as well as when the previous crop had been severely waterlogged (Di Bella, Stringer, Wood, Royle & Holzberger, 2008). In South Africa profuse flowering in the northern regions and coastal regions of KwaZulu-Natal can be the cause of yield losses in crops harvested during late summer (Donaldson & Singels, 2004). Combined commercial data and data from well executed field experiments in Zimbabwe showed that sugarcane yielded best from crops ratooned in April to June after which there was a sharp decline to December ratoon crops. Flowering and lodging were not present and were therefore not associated with the poor yields of crops started in summer in a study of seasonal yields in Zimbabwe (Sweet & Patel, 1985). The authors attributed the better growth of autumn/winter started crops to the optimum growing conditions that such crops experience for most of the cycle. The poorer growth of the summer started crops was thought to be due to the restriction on growth imposed by low winter temperatures. They noted that sucrose content peaked in July/August (Sweet & Patel, 1985). A recent study of the effect of time of ratooning on sugarcane growth in the Burdekin region of Australia provided good evidence of higher annual yields in crops started in April and May compared with November/December ratoon crops (Mc Donald, 2006). The April/May crops would have experienced low winter temperatures during very early growth stages compared to the November/December ratoons having experienced winter from the age of 6 months. It has been well documented in a review by Sinclair & Muchow (1999), that crop biomass production was linearly related to cumulative intercepted solar radiation. However, several studies most notably that by Muchow, Spillman, Wood & Thomas (1994) showed that growth of crops was markedly slower than during the final few months before the normal harvest date. The findings of Park, Roberston & Inman-Bamber (2005) from a comprehensive review of growth experiments in Australia were that lodging and stalk death were associated with the reduced growth phenomenon (RGP) in older crops, although there were several instances where RGP was not associated with lodging. Many physiological factors point to potentially high yields from summer harvested crops and this is evidenced by rapid early growth. However, there is also the contradictory evidence of poor yields in these late summer crops. Crops that start growing at different times of the year experience changes in temperature and solar radiation that are characteristic to each starting time. As biomass increases, the stalk fraction in the biomass increases and the fraction of foliage decreases. The stalk and foliage fractions in annual crops vary through the season. The

highest stalk fractions in annual crops were attained in June ratoon crops (0.78) and the lowest in March ratoon crops (0.57) (Singels, Donaldson & Smit, 2005a). This was due to differential sensitivities of leaf and stalk growth to temperatures (Lui & Bull, 2001). Season also has an influence on the way dry matter is partitioned to sucrose; rising from autumn months to peak in July and decreasing into summer month (Inman-Bamber, Muchow & Robertson, 2002). There is thus evidence that many facets of sugarcane growth are strongly influenced by seasonal variation in temperature.

The term radiation use efficiency (RUE) is used to describe the accumulation of plant biomass in relation to the amount of intercepted solar radiation. As mentioned before, the photosynthetic processes are mainly driven by the blue and red radiation spectra. However, RUE was shown to increase when the diffuse fraction of incident radiation was increased in row crops (Sinclair, Tatsuhiko & Hammer, 1992). Both quantity and quality of radiation therefore affect growth of plants. The literature abounds in examples of how plant growth is modulated by phytochrome-mediated responses to radiation quality and day length. Supplemental far-red radiation, typical of shaded conditions within a crop stand, increased leaf length without affecting the period required to produce a leaf of spring barley (Skinner and Simmons, 1993). It is commonly believed that reduced leaf growth in plants exposed to low red (R) to far-red (FR) ratios (R:FR) is a consequence of increased stem growth (Yanovsky, Casal, Salerno & Sánchez, 1995). Leaf senescence was accelerated in lower levels of plant canopies where PAR and R:FR was low (Ballaré and Casal, 2000). Changes in temperature and daylength had opposite effects on phyllochrons of winter wheat and spring barley (Jame, Cutforth & Ritchie, 1998). Phyllochrons shortened as daylength increased at a given temperature and phyllochrons also shortened as temperature decreased at a given daylength. Davis & Simmons (1994) showed that altered radiation quality, especially R:FR, played a role in suppressing tillering in barley. The beginning of tiller death in winter wheat was triggered by changes in R:FR at the base of the canopy, rather than the interception of radiation by shoots. This points to radiation quality being the key factor that initiated tiller senescence in wheat (Sparkes, Holme & Gaju, 2006). A recent review of the effects of radiation on plant growth by Folta & Maruhnich (2007) suggested that green spectrum of radiation opposed effects directed by blue and red wavelengths to orchestrate development and growth of plants. Plant growth and development that is primarily driven by temperature appears to display considerable plasticity in response to

phototropic or phytochrome-mediated stimuli. In the present study radiation quality was not measured and attempts at showing associations between radiation quality and plant development and growth in this thesis are only speculative; they may none-the-less have been the reason for unexpected deviations observed in growth patterns.

Descriptions of the components of the sugarcane canopy and their rates of development at different seasonal starting times will provide information that is essential in improving the knowledge needed to unveil the mechanisms of radiation capture and hence biomass production. Lack of information on these aspects was the motivation for this study. The study therefore attempts to describe leaf and shoot development, the accumulation of biomass and the fraction of foliage, fibre and sucrose in biomass over time of three cultivars that started growing during different times of the year. The relationships between intercepted solar radiation, temperature and biomass accumulation of three morphologically different cultivars ratooned in different months was the main focus of the study.

A simplistic framework used in analysing the data is: The fraction of solar radiation that is intercepted by the crop depends on the development of the crop canopy. The first product of photosynthesis is sucrose which is hydrolysed to produce energy and tissue components for the production of leaves, stalks and roots which are mainly fibre. The hydrolysed sucrose forms a pool of monosaccharides which are drawn into energy and tissue production processes. The sucrose that remains after consumption by growth and maintenance respiration is stored in the stalk parenchyma. Photosynthesis and the partitioning of sucrose to each end product, namely roots, foliage and stalks are temperature sensitive processes. The allocation of assimilate to the components of above-ground biomass are therefore governed by temperature.

The recent identification of “feedback” signals operating in sugarcane (Mc Cormick *et al*., 2006) introduces a new dynamic to this framework and new insights, particularly related to cultivar responses to temperature and radiation, are being sought. Together with data from similar studies at different sites the present study can be very useful in identifying stable genetic coefficients that may be useful for modelling (see Donaldson, Redshaw & Singels, 2003).

The overall objective of this study was to find simple physiological and morphological reasons for differences amongst cultivars and crop starting times in the way biomass is accumulated and dry matter is partitioned. The reasons for differences in biomass accumulation and dry matter partitioning need to be understood in order to determine how to improve efficiencies of radiation interception, and partitioning of photo-assimilate to the vegetative components and to storage. An understanding of these factors will enable an educated choice of cultivar-type and starting dates for farm production of the crop. Specific objectives were:

1) to determine whether three commercial cultivars were morphologically different in their canopy development and if canopies intercepted radiation differently during early crop development, and what effects starting time had on canopy development and radiation interception among different cultivars;

2) to determine whether the partitioning of photosynthate between foliage and stalks (culm) was different among cultivars and how this was influenced by crop start date;

3) to determine how dry matter was partitioned within stalks of different cultivars and how this was affected by the season through which they grow; and

4) to determine whether cultivars have different RUEs and whether this is influenced by the time of year (season) when the crops start to grow.

CHAPTER 2

METHODS

2.1 **The site**

The experiment was sited on the Experiment Station Research farm of the South African Sugar Association at Pongola (27°25' S, 31°36' E), Kwa-Zulu Natal. The soil at the site was a deep sandy clay loam soil of which the physical and chemical characteristics have previously been described by Thompson and Boyce (1968) and presumed not to change over long periods (Thompson, 1991).

2.2 **Treatments**

2.2.1 Cultivars

All experimental plots comprised 12 rows of sugarcane spaced 1.4 m apart. The row length of the NCo376, N25 and N26 cultivar plots was 23 m while the plots of the other cultivars were 18 m long (Appendix 1(a)). Each of 5 blocks (310 -314) was divided in half and each half was designated with one of five crop start dates, namely March, April, May, August and December (Appendix1(a)). Crop start dates were therefore replicated twice. Each starting-time block was planted to five cultivars. The cultivars NCo376, N25 and N26 were common to all starting times. In addition, the cultivars N22 and N19 were planted in the March and December blocks. CP66/1043 and N24 were planted in the April and August blocks. The additional cultivars in the May block were N17 and Q124. The cultivars NCo376, N17 and N25 are known to have relatively low sucrose content at the age of 12 months during autumn months. CP661043, N24, N19 and N22 mature well in autumn months and are known to have higher sucrose contents than NCo376. The cultivar Q124 was a popular commercial Queensland (Australia) cultivar until it succumbed to disease (yellow leaf syndrome). The experiment of 50 plots with breaks between plots and half blocks covered an area of 1.89 hectares.

2.2.2 Crop start dates – second ratoon (R2)

After 8 months of growth the plant crops in plots designated to be started in May, August and December were all cut back between 10 and 12 November, 1997. Thereafter the May crops were started when the growth between November 1997 and May 1998 was cut back on 6 May, 1998. The August crops were started when the growth between November, 1997 and August, 1998 was cutback on 6 August, 1998. The December crops were started when the growth between November, 1997 and December, 1998 was

cut back on the 8 December, 1998. The March and April crops were started by cutting back the plant crops in these blocks on 5 March, 1998 and on 8 April, 1998. The May, August and December crops were therefore in their second ratoon, whereas the March and April starts were first ratoon crops and it was presumed that they were all physiologically the same. For convenience they were collectively referred to as the second ratoon (R2) (Table 1).

2.2.3 Crop start dates – third ratoon (R3)

The May plots in R2 were harvested at the age of 13 months on 7 June, 1999, which was the start of the June crops in R3. On 6 August, 1999 and 8 December, 1999 plots of R2 were harvested at the age of 12 months in 1999 to start the August and December crops of R3. The March and April plots were harvested at the age of 15 and 14 months, respectively, on 8 June, 1999. The March crops of R3 were started by cutting back the nine-month old growth (June, 1999 – March, 2000) on 8 March 2000. Similarly, the April crops of R3 were started by cutting back the 10-month old crop (June, 1999 – April, 2000) on 6 April 2000 (Table 1).

Table 1 Starting and completion dates of sugarcane crops in the second (R2) and third (R3) ratoons.

R2	Starting date	Completion date	Crop age (days)	Crop age (weeks)
March	5 March, 1998	30 March, 1999	390	56
April	8 April, 1998	4 May, 1999	391	56
May	6 May, 1998	7 June, 1999	397	57
August	6 August, 1998	6 August, 1999	365	52
December	8 December, 1998	30 November, 1999	357	51
R3				
March	8 March, 2000	6 March, 2001	363	52
April	6 April, 2000	3 April, 2001	362	52
June	7 June, 1999	1 June, 2000	353	50
August	6 August, 1999	1 August, 2000	360	51
December	8 December, 1999	11 December, 2000	368	53

2.3 **Husbandry practices**

2.3.1 The plant crop

All previous plant growth in five blocks, each 300m long and 18m wide, was killed with glyphosate. After a fallow period of three months the soil was ploughed and harrowed to a fine tilth for planting on 12 March 1997. Shallow planting furrows, spaced 1.4m apart, were drawn in a north – south direction. Plots were demarcated and sign-posted for clear identification of cultivar and plot number. Fertilizer applied as ammoniated superphosphate (16) + Zn (0.5) was evenly spread in the furrows by hand to each plot to provide 25 kg N ha^{-1}, 79 kg P ha^{-1}, and 3.25 kg Zn ha^{-1}. Disease-free stalks, produced in the farms' nursery, were stripped of green and dead leaf material, topped and then laid in pairs, end to end, in the planting furrow and covered with soil, using hoes. The herbicide mixture of metribuzin (3 L ha^{-1}) + diuron (2 L ha^{-1}) was applied by knapsacks immediately after planting. Five weeks after planting, a few small areas were re-planted where germination was poor. A side dressing of 120 kg N $ha^{-1}$and 120 kg K ha^{-1} applied as a compound (1.0.1(48)) was given to all plots two months after planting. Growth of the plant crop, prior to the start of May, August and December crops of R2 was cut back between 10 and 12 November, 1997 and the re-growth was sprayed with 11.5 kg Zn ha^{-1} as a $ZnSo_4$ solution. A side dressing of 22 kg N ha^{-1}, 44 kg P ha^{-1} and 1.5 kg Zn ha^{-1} applied as a compound was given on 14 January, 1998. Weed growth was suppressed with a single application mixture of MCPA (3 L ha^{-1}) + Gesapax (3 L ha^{-1}) mixture.

2.3.2 Second and third ratoons

Cane tops and trash that were left after harvesting the previous growth were raked and cleared by hand, leaving no plant material in plots. Side dressings of 167 kg N ha^{-1}, 34 kg P ha^{-1} and 167 kg K ha^{-1} (as a compound 5.1.5(46)) and 22 kg N ha^{-1}, 44 kg P ha^{-1} and 3.5 kg Zn ha^{-1} as MAP (33) + Zn (0.75) were given in a narrow band over the row. During the same week a mixture of the herbicides Sencor (metribuzin) (3 L ha^{-1}) and diuron (2 L ha^{-1}) was applied with CP3 knapsacks. Late emerging weeds were eliminated through several hand hoeings. A side dressing of 51 kg N ha^{-1} in the form of urea was given when the crops were 5 months old. The total nutrients applied to these crops therefore were 240 kg N ha^{-1}, 78 kg P ha^{-1}, 167 kg K ha^{-1} and 3.5 kg Zn ha^{-1}. The late application of urea was to correct any loss of nitrogen from the root zone that may have been caused by over irrigation. The relatively high P applications and Zn to the

ratoon crops were to correct the deficiencies of these nutrients which were detected in third leaf samples of the plant crop.

Third leaf blades from ratoon crops were taken a month after the last fertilizer application. The analysis of these samples indicated that nutrients N, P, K, Ca, Mg and Zn had been taken up in adequate amounts according to the threshold values of the Field Advisory Services of the South African Sugarcane Research Institute. The analysis also showed that deficiencies in Zn in previous crops had been remedied by the additional application of Zn fertilizer. Examples of the good nutrient status of the crops are illustrated by the third leaf nitrogen levels in the second ratoon crops (Figure 1).

2.3.3 Irrigation

The plant crops were initially irrigated with overhead sprinklers to ensure even germination and thereafter irrigation water was delivered through dripper lines with inline-drippers spaced 0.60 m apart. The dripper lines were placed in every alternate row. A profit (rainfall + irrigation) and loss (evapotranspiration) account was kept to maintain a soil water balance. A computerised irrigation scheduling programme (Singels, Kennedy & Bezuidenhout, 1998) was also used to assist with scheduling irrigation. On most occasions 52 mm ha^{-1} of water was applied during 48 hours to keep the crops free of water stress.

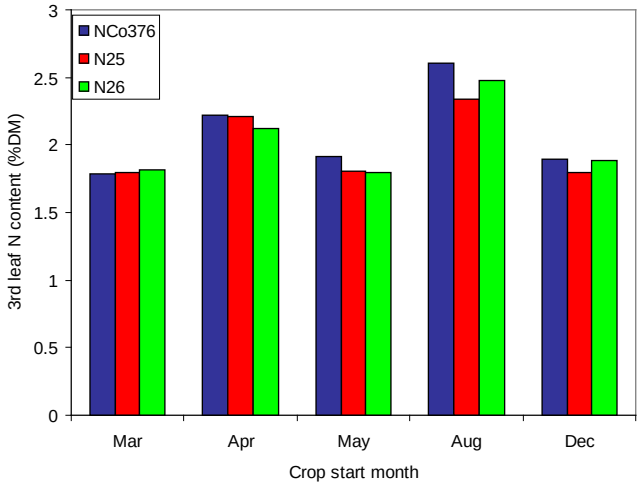


Figure 1 Third leaf nitrogen content (% dry mass) one month after fertilizer application in sugarcane crops of NCo376, N25 and N26 R2 crops ratooned in March, April, May, August and December 1998.

Flow meters were installed at the point of water delivery to each replication, and records of the amounts applied on each occasion were used to assist with scheduling. Soil water levels were estimated based on the total soil available water (TAW) of 200mm (Thompson and Boyce, 1968; Thompson, 1991). The estimated soil water in second ratoon of the December and May ratoons of NCo376 is given as an example in Figure 2. Soil water levels were well above 50% of TAW throughout the crop's growth and only dropped to this level on a few days when both these crops were close to final harvest dates.

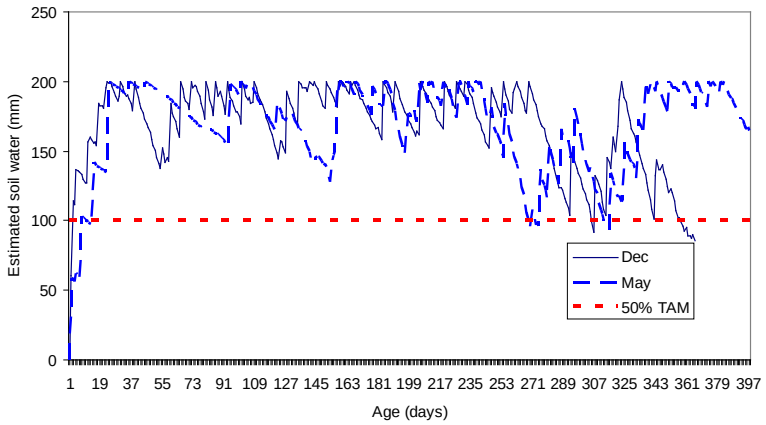


Figure 2 Estimated soil water levels (mm) of the December (solid line) and May (broken line) ratoon crops and 50% of Total Available Water (TAW) during the second ratoon.

2.4 **Measurements**

In-field non-destructive measurements described below were done to enable description of the changes to the canopy brought about by changing shoot and leaf numbers, leaf production rates, and numbers of senescing leaves in relation to five crops starting dates (months). Areas of leaf blades on shoots in destructive samples were taken at pre-determined times. In addition to the destructive sampling leaf blade areas were measured on several other occasions to produce a composite profile of leaf sizes for each cultivar.

2.4.1 Shoot emergence

The number of living shoots was counted in 4 m sections of nine rows (5.6 m²) in each plot every two to three weeks after shoots started emerging. The data from crops in which shoots were first counted relatively soon after the cutback of the previous crop

were used to estimate day on which the first shoot emerged (later described as the pre-emergence phase). This was done by fitting logarithmic curves to stalk densities plotted against time (days) from the cutback date of the previous crop. The value at the intercept was taken as the day on which the first shoots started to emerge. The date of emergence was defined as the day on which one shoot per m row had appeared (Lui, Kingston & Bull, 1998). The March, April, May and December ratoons of R2 and the August ratoon crop of R3 had data close to the starting date and therefore were deemed suitable for estimating the time to emergence. Having found the days to emergence the time was then expressed as cumulative heat units using different base temperatures.

The cumulative heat units affecting the germination process (or any physiological process) are referred to here as thermal time. Heat units (also referred to as growing degree days) are calculated by subtracting the base temperature from the mean daily temperature (maximum temperature + minimum temperature)/2. The cumulative heat units are referred to as thermal time or thermal units (°C d). The germination process is governed mainly by temperature and the duration of the pre-emergence phase can be predicted by describing the period from harvesting to emergence in terms of heat units. This would require knowledge of the base temperature at which metabolic activity, contributing to germination, ceases. Methods used in determining the base temperature for germination (pre-emergence) are described in 3.2.2.

2.4.2 Shoot population dynamics

The number of living shoots was counted in 4 m sections of nine rows (5.6 m^2) in each plot every two to three weeks, until lodging made it difficult to record counts accurately. However, counts between the dates 2 December, 1998 and 31 March, 1999 were estimated for R2 crops when counts were not done, with the exception of the March crops, by fitting 4^{th} degree polynomial functions (Inman-Bamber, 1994b) to the counts made on other occasions. On the final sampling dates careful counts of stalks were made regardless of whether crops had lodged or not. In lodged plots stalks were lifted to separate them so that they were more easily counted. Dates of the start of lodging were also recorded (Appendix 1(c)).

Inman-Bamber (1994b) found the minimum temperature for shoot population dynamics to be 16ºC compared to 10ºC for leaf appearance. Consequently, development of shoot

densities in sugarcane was described in terms of thermal time using base temperatures of 16° C for population dynamics and 10°C for leaf appearance. Data from both R2 and R3 crops were used in Chapter 3 to describe shoot population dynamics.

2.4.3 Leaf appearance and senescence

Ten primary shoots in each plot were tagged for easy identification and the total number of leaves was counted, including the youngest unfurled leaves. The counts excluded the spindle tip. Leaves were counted from the stalk base upwards and leaf number one was taken as the first leaf with a lamina $\geq$ 10 mm long. The number of dead leaves on each stalk was also counted on the same day that shoot numbers were recorded. The tag was moved to a fixed position on the stalk (e.g. between leaf eight and nine) before the first dead leaves at the base of the stalk were dislodged and became difficult to detect. When it became apparent that a tagged stalk was dying, the tag was moved to a healthy stalk of similar size and positioned at the appropriate leaf number. Leaf appearance and death of leaves were related to thermal time and phyllochrons were calculated from the reciprocals of the slopes by regressing leaf appearance with thermal time (base 10°C). A phyllochron was taken to be the thermal time (°C d) between the appearances of two successive leaves (Gallagher, 1979) (i.e. °C d leaf^{-1}).

2.4.4 Leaf blade area and green leaf area index (LAI)

Shoots were selected to represent the range of shoot heights in each of the two 15-shoot samples. At the ages of 4, 8, 10, 11 and 12 months when destructive shoot samples were taken (see 2.6 below), the size of leaves on three shoots from each of the two replications (six stalks) were measured with a Licor 3000 area meter. The leaf blades of these shoots were cut off at the ligules in sequence from the oldest to the youngest leaf, and the areas of individual leaves were measured and recorded in this sequence. On a few additional occasions, the length, width and areas of individual leaves on three shoots from each cultivar were measured. The measurements on these occasions were used to derive the relationship of length and width to area ((L x W)/A) for each cultivar. On occasions when the planometer broke down the length of the lamina and width at the centre of the lamina of individual leaves were measured. The areas (A) of leaf blades for thee occasions were calculated as: (L x W) x the derived factor (Inman-Bamber,1986). The areas of individual leaves on an average stalk were compiled from the leaf area data. The product of shoot numbers per hectare and total green leaf area

per shoot was calculated to give the green leaf area index (LAI) for each date of recording.

2.4.5 Radiation interception by the canopy

A ceptometer (SF-80 ceptometer- Decagon Devices, Pullman, WA, USA) was used to measure the amount of photosynthetically active radiation intercepted (iPAR) by the green leaf canopy, every two to three weeks. Readings were done between 11h00 and 13h00 on cloudless days only. At each plot, a reference reading above the canopy was taken before taking eight readings below the bottom green leaves so that the ceptometer was above any senescing leaves of the canopy. The ceptometer was held horizontally at an angle to the cane rows so that the tip was in the centre of the row and the recording unit was in the centre of the interrow. The instrument was levelled before making a recording.

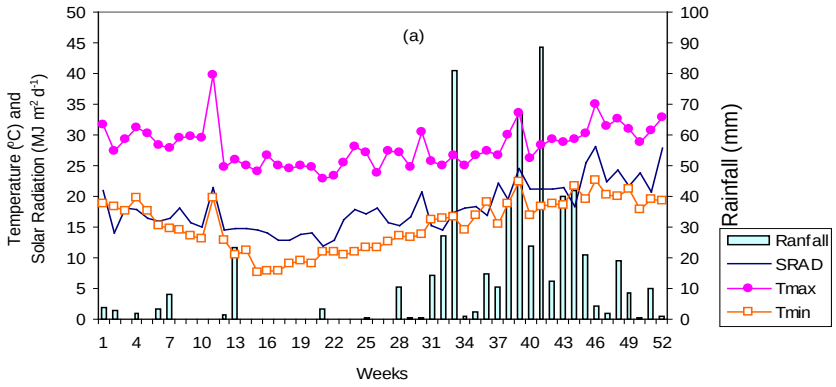
Polynomial functions (Appendix 1(b)) were fitted to the measured fractions of intercepted PAR (iPAR) versus time for each cultivar. These functions were applied to daily incident solar radiation to calculate daily intercepted solar radiation in each crop. Daily interception of solar radiation was estimated by assuming that PAR is 50% of solar radiation (Spitters *et al*., 1986). In all instances it was assumed that a stage was reached when canopy closure was complete and that solar radiation was then fully (100%) intercepted.

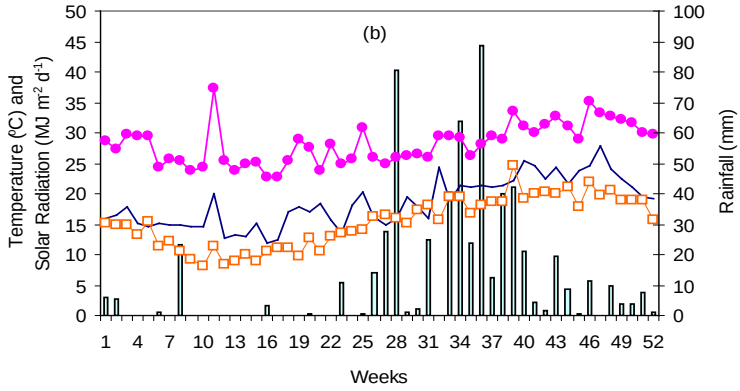
Extinction coefficients (*k*) of NCo376, N25 and N26 were calculated from LAI and fractions of PAR interception (iPAR) taken before decline in LAI by regressing the natural log of fractional iPAR intercepted (1-Li) on LAI. The slope of the linear equation from this regression gives the *k* value. The LAI data from samples taken at 4 months in each of the five crops were used to calculate *k* for each of the cultivars because LAI declined after 4 months in some of the crops.

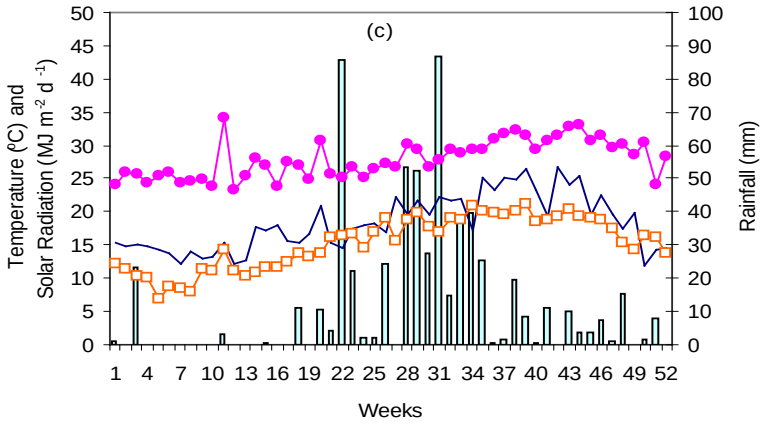
2.5 **Weather**

Maximum and minimum temperatures, rainfall and daily global incoming radiation were recorded during the course of the experiment at an automated weather station adjacent to the experiment.

Weather data showing mean weekly temperatures, solar radiation and rainfall for each of the R2 crops depict the different temperature regimes to which crops were subjected (Figure 3). For example, the low and declining minimum temperatures (range 6 -12°C)







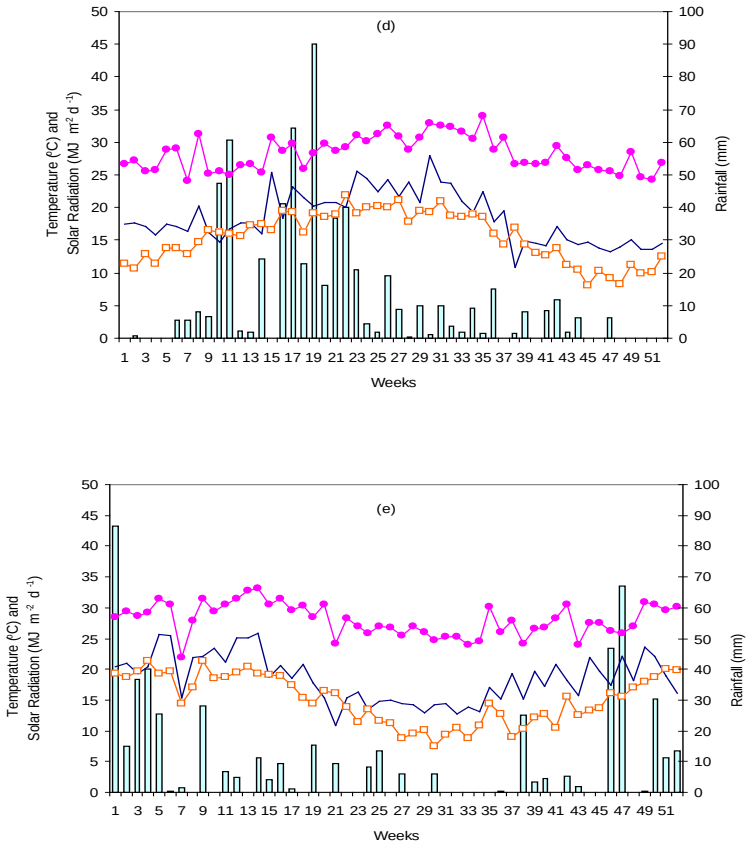


Figure 3 Weekly means of maximum (Tmax), and minimum (Tmin), temperatures and solar radiation (SRAD), and weekly rainfall of second ratoon crops started in (a) March (b) April (c) May (d) August and (e) and December 1998.

during the first 9 weeks of the May ratoon are in contrast to the high minimum temperatures (range 15-22°C) during the same period at the start of the December ratoon. During the first 13 weeks the December ratoons solar radiation was considerably higher (>20 $MJm^{-2}d^{-1}$) than in the crops started in May (about 15 $MJm^{-2}d^{-1}$). The total incident radiation of crops in the R2 crops was substantially higher than in the R3 crops (Table 2). The higher rainfall recorded during the period of the R3 crops is consistent with more cloudy days that would have reduced incident solar radiation. The consequence of this was clearly shown in the lower mean daily incident solar radiation in R3 crops compared with R2 crops (Table 2).

Table 2 Mean daily incident solar radiation (iRad) and temperature (temp) and total incident solar radiation, rainfall and evapotranspiration (Thompson, 1976) for each crop in the second (R2) and third ratoon (R3) crops.

Ratoon	Crop start date	Mean iRad MJ m^{-2} d^{-1}	Total iRad MJ m^{-2}	Total rainfall $crop^{-1}$ mm	Et ref $crop^{-1}$ mm	Mean temp. °C
R2	March	18.00	6 569	589	1 535	21.5
	April	18.35	6 695	607	1 556	21.6
	May	18.29	6 623	620	1 531	21.4
	August	18.33	6 638	627	1 563	21.6
	December	18.53	6 614	581	1 546	21.7
R3	March	16.84	6 131	984	1 379	21.0
	April	16.97	6 162	887	1 388	21.2
	June	17.64	6 315	1238	1 430	21.2
	August	17.53	6 347	1237	1 410	21.1
	December	16.79	6 182	1472	1 364	21.1

2.6 **Destructive sampling**

Samples of whole plants (shoots) were taken at different ages to describe biomass accumulated as green foliage, trash, stalks and meristems. Analysis of whole stalks (culm) and stalk sections were done to describe partitioning of dry matter components in different sections of the stalk over time.

On predetermined dates when the crops were about 4, 8, 10, 11 and 12 months old, samples of stalks and trash (as described below in 2.6.1 and 2.6.2) were taken at four predetermined positions in each plot (Appendix 1(d)). The final samplings of the March, April and May crops were at the age of 13 months and that of August and December crops was at the age of 12 months in R2. The sampling points were positioned to minimise disruption of the radiation environment on un-sampled areas. This was achieved by leaving a 1.0 m buffer area between sampling points and not sampling within 2.0 m in adjacent areas of neighbouring cane rows.

2.6.1 Trash

The trash around the 15 adjacent living stalks that were identified for sampling was collected. Samples of trash consisted of all the dying leaves on the 15 sampled stalks. A

leaf with more than 50% of its area either dead or yellowing was considered part of dead trash. Also included in the sample were all dead and dying shoots, in the area occupied by the 15 stalks (at four points). Dying shoots were identified by their dead uppermost leaves and dead or dying spindle. Trash samples were therefore made up of dead and dying leaves and dead as well as dying shoots, some of which had stalks. The samples were weighed and cut to size for drying in trays. The representative sub-samples of about 500g of shredded trash were dried at 80°C in trays for about 18 hours before being weighed again to determine the dry mass and to calculate total dry mass per plot. The presence of stalk material in trash samples may have caused lower dry matter contents to be determined in trash than when no stalks had senesced. Trash material was cut to size but was not shredded before drying. Bulky parts of the trash may not have dried to constant mass and therefore estimated dry matter content would have been over estimated, particularly by the presence of stalk material.

2.6.2 Meristem, stalk and foliage fresh mass

After collecting the dead trash around the 15 shoots, the shoots were cut at ground level using a curved-blade saw. The samples of 15 shoots with all their green leaves attached were bundled and weighed. The lengths from the base to the last visible collar (also called the top visible dewlap) of ten stalks in each sample were measured. One of the four samples from each replication was set aside to measure leaf blade areas and to determine dry mass of blades and sheaths. The remaining three samples were used to determine foliage and stalk fresh mass. Each sample of shoots i.e. stalks with green foliage still attached, was weighed. The foliage was then stripped from the stalks and the cleaned stalks were then also weighed. The immature sections of stalk below the stalk apex that broke off during this procedure were weighed separately. The mass of the green foliage was derived from the difference between the mass of the shoots with attached green foliage and the mass of cleaned stalks. The total of the combined fresh leaf blades and sheaths mass was divided by their total combined dry mass to calculate foliage dry matter content.

2.6.3 Stalk emergence

During the development of the March, April and August ratoons shoots with leaves numbering from 4 to 14 were taken randomly, taking care to avoid areas designated for sampling and shoot counts. Each shoot was carefully cut at the base of the shoot and

care was taken to retain all leaves in position on the shoot with a rubber band. The number of leaves for each shoot was then recorded and the presence or absence of a stalk apex was recorded.

2.6.4 Stalk sucrose and brix contents

Each sample of fifteen cleaned stalks was shredded with a modified wood planer and divided into two sub-samples. One sub-sample was weighed, oven dried for 18 hours at 80°C and weighed again. The second sub-sample was macerated in 1.0 L of water with an Ultra-turrax homogeniser. The homogenised juice solution was filtered and clarified. One sub-sample was analysed for the amounts of soluble solids (brix) with a refractrometer and a second sub-sample was analysed for sucrose concentrations with a saccharimeter (Buchanan & Brokensha, 1974; SASTA, 1985).

2.6.5 Meristem, blade and sheath dry mass

Three shoots were selected to represent the range of shoot lengths in one of the 15-shoot samples. After removing the green leaves, meristems were located by oblique dissection. The leaf material in the leaf roll above the meristem was cut off and added to leaf laminas for fresh and dry mass determinations. The top immature section of each stalk was broken off and these were combined into a single sample (per cultivar and ratoon date). Leaf laminas, sheaths and immature stalk tops were weighed separately, oven dried for 24 hours and then weighed again to determine dry mass from which dry matter content could be calculated. The remaining 12 shoots were used to determine the fresh mass of leaf laminas, sheaths and stalks.

2.6.6 Stalk sectioning

Fifteen cleaned stalks from each of the two replicates were then combined into a 30-stalk sample and sectioned as follows:

Base to 0.20 m up the stalk
Apex to 0.20 m down the stalk
0.20 m to 0.40 m up from the base
0.20 m to 0.40 m down from the apex
Mid section *
0.40 m to 0.60 m up from the base
0.40 m to 0.60 m down from the apex

*Any remaining part was assigned as a mid-section (of variable length)

Sections were weighed and analysed to determine dry matter content, brix, fibre and sucrose contents as for the whole stalks.

2.7 **Statistical analysis**

Yield data were analysed using residual maximum likelihood (Genstat, 10th Edition, VSN International Ltd, 2007) to determine standard error of differences for cultivars and harvesting cycles. Components of yield were analysed using analysis of variance and the Chi square test at the 5% significance level. Summaries of statistical analyses of selected components are shown in Appendix 1 (e,f,g). The analysis in Tables e and f of Appendix 1 included data from all ages. The analysis in Table g of Appendix 1 was done on data of trash from the 12-month old crops which are presented in Chapter 6. Polynomial or linear functions were fitted to some data to reveal general trends and rate changes in processes and data have been presented in graphs. Polynomials have also been fitted to population density data to describe natural growth processes of shoot emergence followed by shoot senescence (Inman-Bamber, 1994b). Statistical analysis was not always possible because of the few data collected in some instances because of limited resources and high expenses in an experiment of this size. However, valuable observations were made from the little data on some occasions and they have been presented graphically, especially in the early chapters. Shoot numbers were counted in R3 and R2 to describe shoot density dynamics. No other data from the R3 crops are presented in this study.

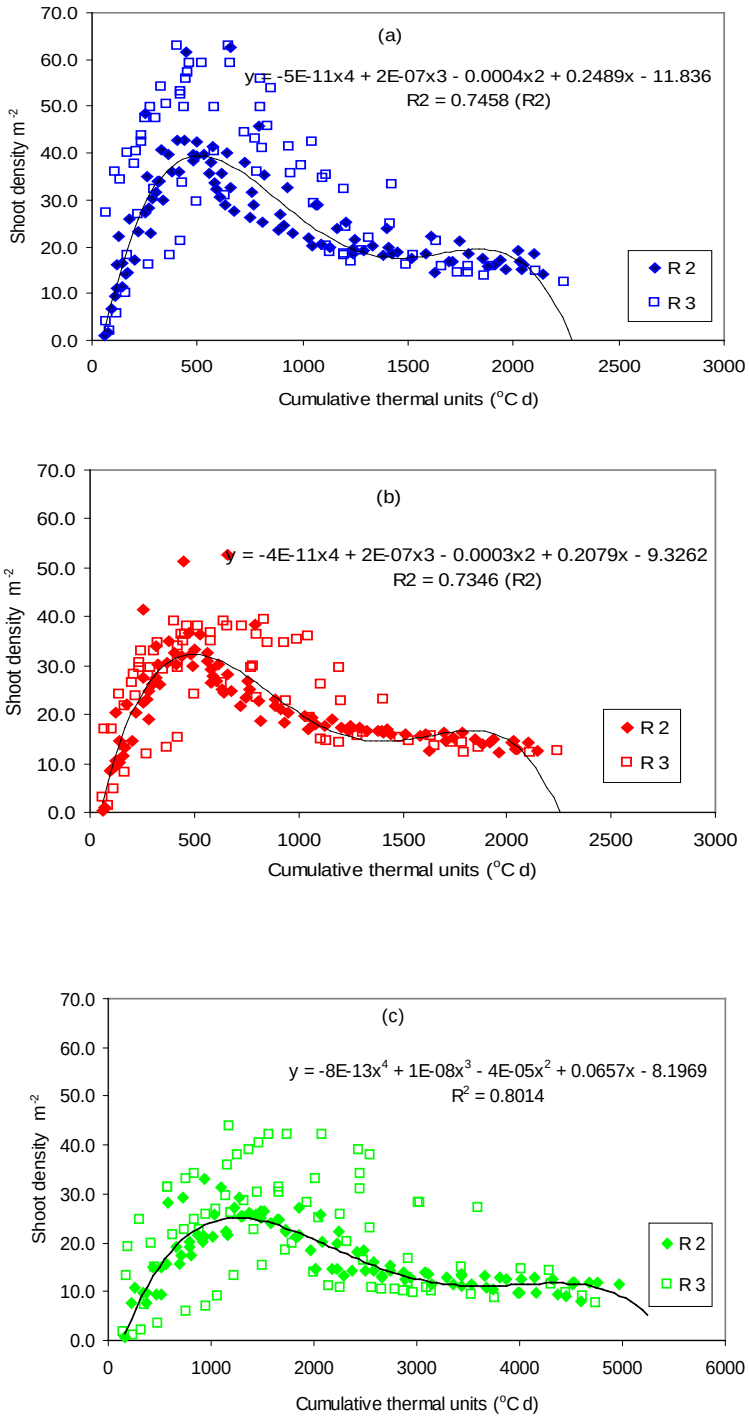


Figure 4 Shoot densities of R2 (closed symbols) and R3 crops (open symbols) of cultivars (a) NCo376, (b) N25 and (c) N26 and cumulative thermal units (°C d) derived from base temperatures of 16°C for NCo376 and N25 and 9°C for N26 from March, April, May, (June for R3), August and December ratoons.

CHAPTER 3

SHOOT POPULATION DYNAMICS

3.1 Introduction

The unit of population dynamics in many tufted grasses, including sugarcane is the tiller. Primary shoots and all secondary tillers are collectively here referred to as shoots. In tufted grasses new shoots develop close to the primary shoot (or parent stem). In sugarcane a tuft is known as a stool. Individual identities of primary and secondary shoots are lost in ratooning sugarcane crops because of the rapid rate of shoot emergence. Stools also loose their individual identity in ratoon crops because of the close spacing of buds on vegetative setts at planting and the prolific tillering in most sugarcane cultivars. The number of shoots and the rate at which they are formed together with L (green leaf area per shoot) largely determine the rate of canopy development and therefore the amount of radiation that is intercepted. Only a relatively small number of the total shoots that are produced survive to the final harvest date. The effects of season on shoot population dynamics, which includes shoot emergence, the number and rate at which they are produced and shoot senescence, need to be understood and related to temperature, time and ultimately to biomass production.

3.2 Results and Discussion

3.2.1 Development of shoot populations

The base temperature (Tb) of each cultivar was determined by iteration using increments of single units of temperature from 0 to 20°C. The maximum R^2 values, derived from 4° polynomial functions (Inman-Bamber, 1994b) fitted to shoot densities versus cumulative thermal units, were deemed to indicate the appropriate base temperature (Table 3). Shoot densities of the R2 and R3 crops (Figure 4) from all five

Table 3 R^2 values of polynomials describing shoot densities in relation to cumulative thermal units in the R2 crops using different base temperatures (°C) for crops started in five months of three cultivars. Highest R^2 values are bold and underlined.

Base temp. (°C)	14	15	16	17	18
NCo376	0.6901	0.7246	**0.7458**	0.7338	0.6883
N25	0.6909	0.72	**0.7346**	0.7157	0.6655
Base temp.	7	8	9	10	11
N26	0.7998	0.8011	**0.8014**	0.8011	0.796

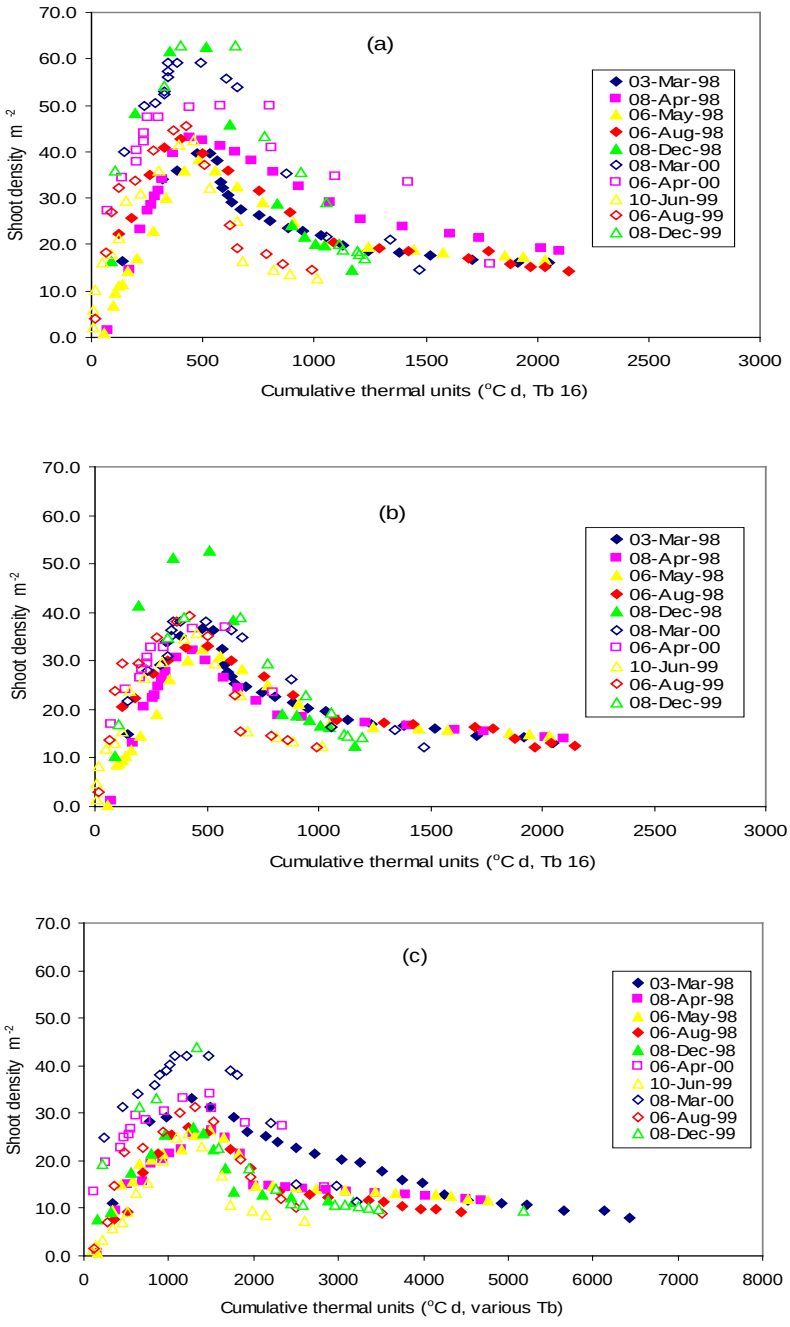


Figure 5 Shoot densities (shoots m^{-2}) of five starting dates for R2 crops (closed symbols) and R3 (open symbols) for (a) NCo376, (b) N25 and (c) N26 and cumulative thermal units with base temperatures 16°C (NCo376 and N25) and mainly 9°C (N26).

starting dates (ratoons) were related to thermal time using the derived Tb of 16°C for both NCo376 and N25 and 9°C for N26 (Table 3). Peak shoot densities of the different ratoon dates also lined up best using Tb 16°C for NCo376 and Tb 9°C for N26 (Figure 5). Inman-Bamber (1994b) also found the appropriate base temperature to be 16°C for both NCo376 and N12.

3.2.2 The shoot pre-emergence - phase 1

The pre-emergence phase described herein includes the pre-germination phase described by Bezuidenhout, O'Leary, Singels & Bajic (2003). The number of days from crop start to emergence (defined as the day on which the number of shoots emerged was equal to, or less than, one shoot m^{-2} (Liu *et al*., 1998) varied according to crop start dates. Emergence took on average (over cultivars) 5 days in March ratoon crops. It took longer in April and May ratoon crops; increasing to 11 and 15 days, respectively. (Figure 6). Thereafter time to shoot emergence decreased to an average of 14 days in August ratoon crops and took 8 days in December ratoon crops. Measurements of the first shoot counts of the August R2 crop were delayed. Hence it was deemed that the August R3 crop gave a better estimate of time of shoot emergence for an August crop start and these data were used in place of the August R2 data (Figure 6).

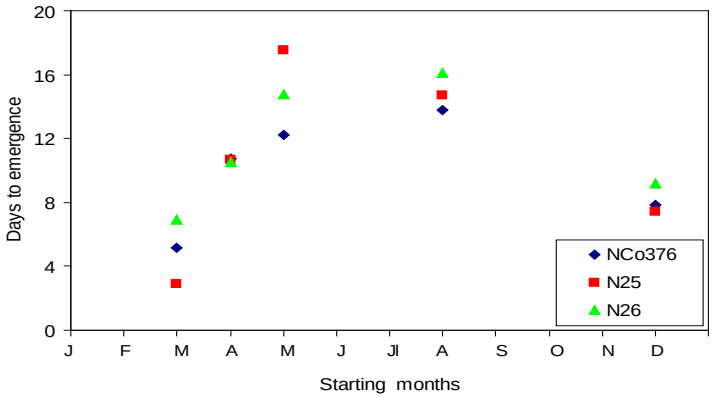


Figure 6 Days to emergence of NCo376, N25 and N26 for crops started in five months of the season.

The number of days to emergence of NCo376, N25 and N26 were regressed on the mean air temperature during the days leading up to the day of emergence of the R2 crops, excluding the August ratoon crops. This was compared with the regression on mean soil temperature taken at 50 mm depth. The depth of 50mm was chosen because

it is at this depth at which the setts were planted and where most of the meristematic tissue of the new growth in the ratoons could be located. Similar R^2 values for time to emergence vs air temperature or soil temperature indicated that the soil temperature was not better related to emergence than air temperature and therefore either could be used for describing shoot emergence in models with equal accuracy (Figure 7). The bare soil temperature at 50 mm depth in the meteorological site was considerably higher than air temperature. Soil temperature in the experiment site could be expected to have been somewhat lower than soil temperature measured in the meteorological site because it was dampened by regular application of irrigation water which would have caused evaporative cooling. The regression in Figure 7 suggests that 84% of the variation in time to emergence of NCo376, N25 and N26 can be attributed to temperature during the

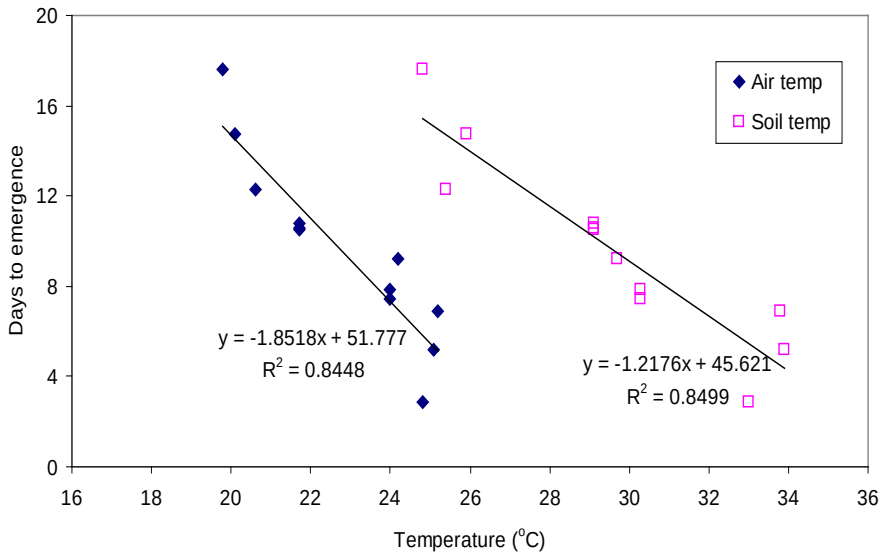


Figure 7 Mean soil (bare soil) at 50 mm depth and air (screen) temperatures during the period from crop start to emergence in relation to days taken to emerge for crops started at different times of the year of R2 cycle.

period leading up to emergence. Days to emergence were then expressed in terms of cumulative thermal units using the base temperatures of 16 and 10°C (Figure 8). The relative variation from using 10°C as a base was less than when 16°C was used for the base temperature. This suggests that the base temperature for this phase from the start of the crop to the emergence of the first shoots is closer to 10ºC than 16°C. The formula for the least standard deviation in days method, described by Yang, Logan & Coffey

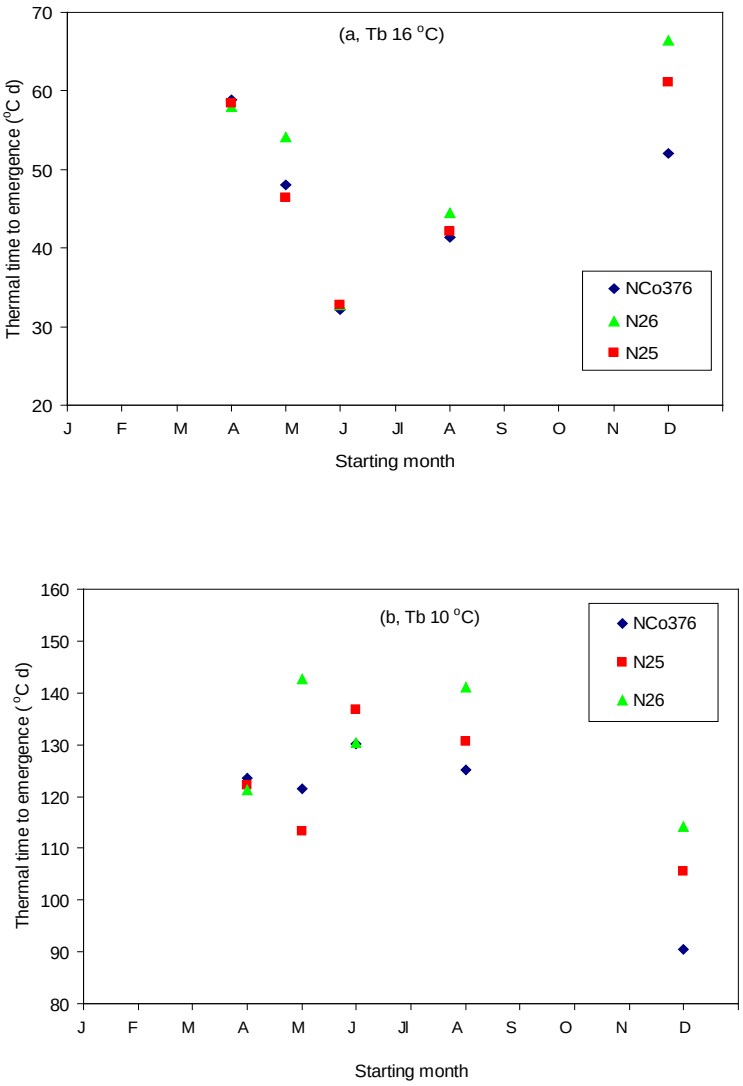


Figure 8 Cumulative thermal time calculated using Tb of (a) 16ºC and (b) 10ºC from starting date to emergence of cultivars NCo376, N25 and N26 for crops started in April, May, June, August and December.

(1995) was used to determine the most appropriate base temperature for each of NCo376, N25 and N26.

Their formula: $x = T - \frac{(\sum^{n}_{i=1} t_i d_i)^2 - n \sum^{n}_{i=1} t_i^2 d_i^2}{n \sum^{n}_{i=1} d_i^2 t_i - n \sum^{n}_{i=1} t_i d_i \sum^{n}_{i=1} d_i}$

where d_i is the number of days required to reach a developmental stage for the *i*th planting; t_i is the difference between the overall mean of temperature during emergence in all ratoons and the mean temperature of the *i*th ratoon; *T* is the overall mean temperature of all ratoon crops; *n* is the number of ratoon crops. The formula required the number of days to emergence and the mean temperature during these days from which the base temperature (*x*) of the specific developmental process was calculated. The base temperatures for NCo376, N25 and N26 were calculated as 12.7, 12.4 and 10.8ºC, respectively, with data from April, May, August and December R2 and June R3 crops (Appendix 5). The June R3 data were included to increase the range of temperatures in the analysis. The calculated base temperature for each cultivar was then used to estimate the cumulative thermal time from cutting to emergence of the first shoots in R2 crops. This is depicted in relation to starting month (Figure 9). There was less variation in the cumulative thermal time for NCo376 amongst the five starting times when a base temperature of 12.7°C was used than when 10ºC was used (Figure 8).

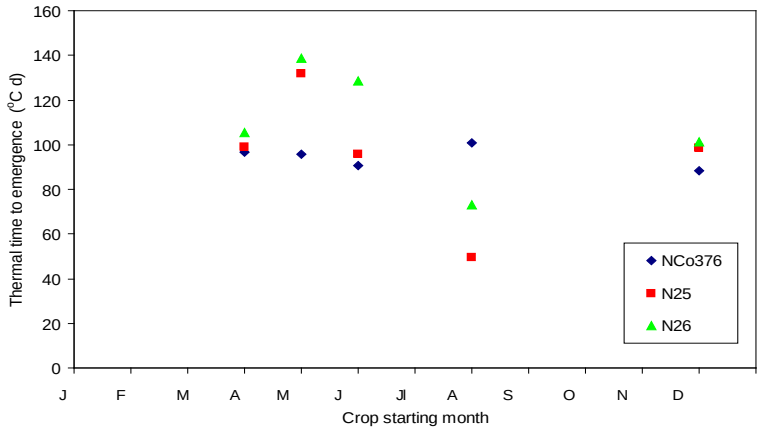


Figure 9 Cumulative thermal time from crop starting date to emergence using base temperatures of 12.7, 12.4 and 10.8ºC for NCo376, N25 and N26, respectively, for crops started in March, April, June, August and December.

Using the above new base temperatures (Figure 9) and excluding the extreme values in the N25 and N26 data, the average cumulative thermal times for the pre-emergence phase of the ratoons were 94.4 ± 6.05, 97.8 ± 16.31 and 115.2 ± 10.45 ºC d for NCo376, N25 and N26, respectively. The values for NCo376 and N25 were not significantly different and their mean thermal time for the pre-emergence phase was 96.2 ± 6.29 °C d. These values are considerably lower than the 203°C d (base 10°C) calculated for

buds 100 mm below the soil surface (Bezuidenhout, 2000). In the present study of ratoon crops, buds are likely to have been closer to the soil surface. More appropriate base temperatures might be derived from careful recordings of the emergence events rather than estimating shoot emergence from shoot density counts as was done in this study.

3.2.3 Shoot emergence - phase 2

Shoot emergence was characterised by the typical rapid increase in shoot numbers within a relatively short period from crop start to a peak shoot density. The maximum shoot densities (SDmax) ha^{-1} of NCo376, N25 and N26 for five starting months of R2 and R3 crops are listed (Appendix 2(a)). The highest shoot densities were developed by NCo376 in the December ratoon crops – having developed SDmax of 62.7 $\pm$ 1.71 m^{-2} and 62.9 $\pm$ 1.01 m^{-2} in the R2 and R3 crops, respectively. In comparison N26 December ratoons developed shoot densities of 32.9 $\pm$ 1.14 m^{-2} and 47.1 $\pm$ 3.86 m^{-2} in R2 and R3 crops, respectively. N26 had the lowest average SDmax of 27.8 $\pm$ 0.97 m^{-2}. The May ratoon crops generally had lower shoot densities than the June ratoon crops. However, SDmax of N26 recorded in the June ratoon of R3 was 54% higher than in the May ratoon crop of R2. On average NCo375 SDmax was significantly (P=0.01) higher than N26. SDmax of December crops were significantly (P=0.01) higher than April, May and August ratoon crops. The mean of NCo376, N25 and N26 (Figure 10) shows peak shoot

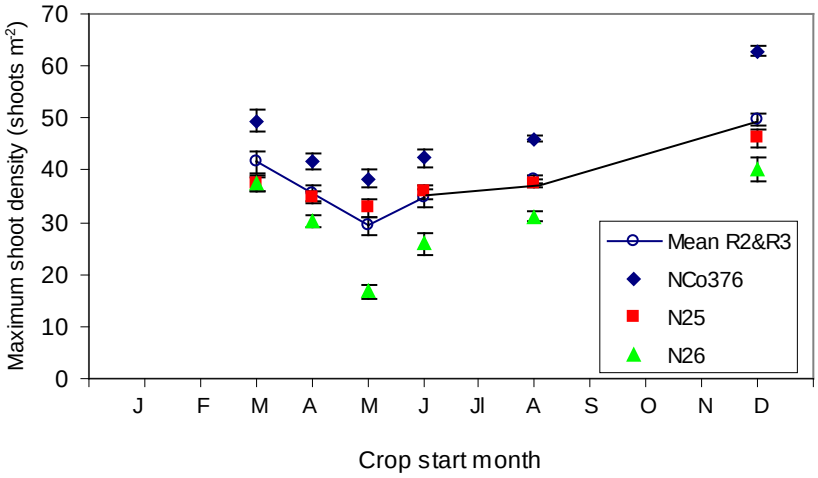


Figure 10 Maximum shoot densities (SDmax) of five starting months from R2 and R3 crops with the mean of NCo376, N25 and N26 shown as the trend line. (Statistical analysis of SDmax is in Appendix 2a). Bars denote standard deviations.

densities were lower in April and May than in March, and were progressively higher in later ratoons (June to December). The average daily mean temperature from emergence to peak shoot densities was 18.8ºC in the May ratoon crop and 19.7ºC for the June ratoons. The seasonal trend was very evident in NCo376 and N26 but less in N25 which also had less seasonal variation in SDmax. When the development of shoot densities were described in terms of cumulative thermal units (Inman-Bamber, 1991b, 1994b) the peaks of NCo376 and N25 occurred, on average, at 509 and 579ºC d (Tb = 16) in the R2 and R3 crops, respectively (Figure 11). N26 stalk densities peaked at about 1385

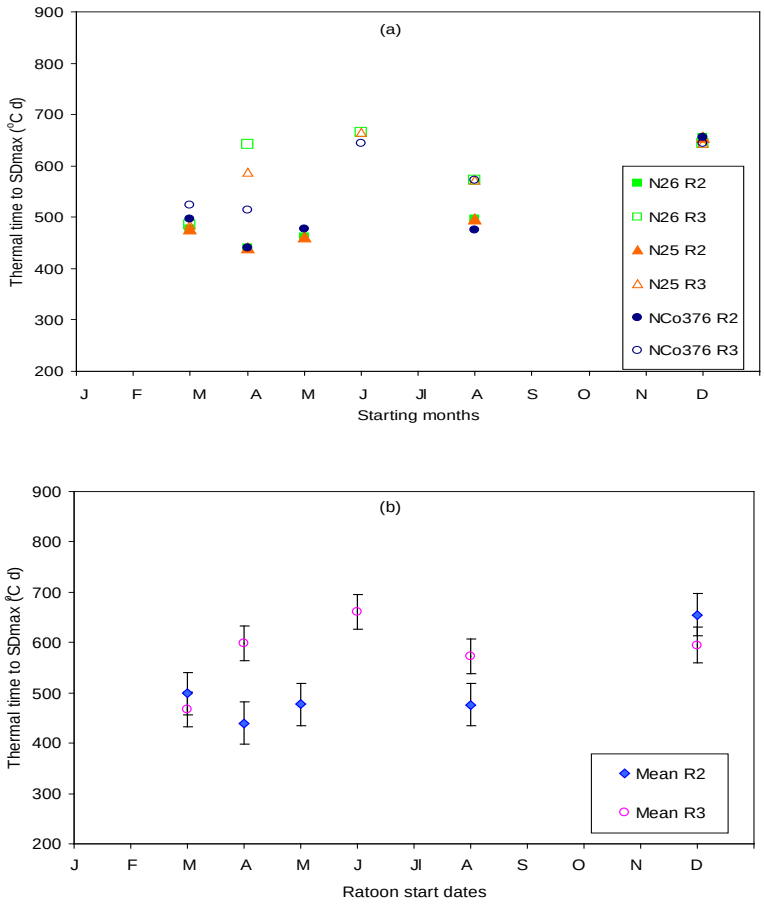


Figure 11 Cumulative thermal time (°C d) thermal base 16°C from starting date to maximum shoot density (SDmax) for (a) NCo376, N25 and N26 and (b) the means of nine cultivars for each starting date of second (R2) and third (R3) ratoon crops. Bars denote standard errors (P=0.05).

and 1330°C d for the R2 and R3 cycles, respectively (Tb = 9°C) (data not shown). Shoot densities peaked later in the December R2 crops than in other starting times. The

cumulative thermal units to SDmax of the December crops for both R2 and R3 could have been over estimated. This was because the time intervals between shoot counts were too long and shoot numbers were changing rapidly so that the true peak densities may not have been recorded. The values are therefore likely to be between 655ºC d and 399ºC d recorded in the R2 and R3 ratoons of NCo376, respectively. When the December data were excluded the average cumulative thermal times to peak shoot densities were then 473 and 579ºC d for the R2 and R3 crops, respectively. The averaged thermal time to SDmax of starting times for the cultivars NCo376, N25 and N26 were very similar for the R2 ratoons (497 $\pm$ 50.29, 506 $\pm$ 42.19 and 506 $\pm$ 42.19 ºC d for NCo376, N25 and N26, respectively (Figure 11). In the R3 ratoons the thermal times to SDmax were longer and differed substantially from each other. When thermal units from emergence to SDmax were accumulated, rather than from starting date to SDmax, there was a slight reduction in the thermal time to SDmax. This, however, had little effect on the seasonal trends (Figure 11) and thermal time to SDmax of May and June ratoons was still longer than the March and April and August ratoon crops, in the R3 and not in R2 ratoon crops. The mean thermal times from ratooning date to SDmax of the R2 crops were similar when the December crops, which were not accurately recorded, were excluded. The cultivars NCo376, N25 and N26 differed widely in thermal times (Tb = 16) to SDmax of the April crops (Figure 11 a), particularly in the R3 crops, but did not differ much in the other starting months. The reason for this is not immediately apparent. Cumulative thermal times from crop start dates to SDmax are shown in Appendix 2(b). Data in R3 crops (Figure 10 and Figure 11) suggest that May and June ratoon crops attain lower SDmax and require more thermal units to reach SDmax than March, April and August ratoons. It is possible that emergence of shoots is governed by temperature and day length or radiation quality.

The shoot development of NCo376, N25 and N26 for each of the five ratoons in each of the R2 and R3 cycles in relation to cumulative thermal units showed that the development of shoots can be described by three phases namely, a pre-emergence phase (phase 1), an emergence phase reaching a peak shoot density (phase 2) and a decline phase during which shoot numbers decrease and then become relatively stable (phase 3) (Figure 12). Two distinct rates of appearance during phase 2 were displayed in the R3 crops. Phase 2 sub 1 is defined as the period during which primary as well as higher order shoots appear. Phase 2 sub 2 has been postulated to be associated with

the appearance of only higher order shoots (Bezuidenhout *et al*., 2003) (Figure 12). Linear regressions were fitted through each sub phase 2 to estimate the rate at which

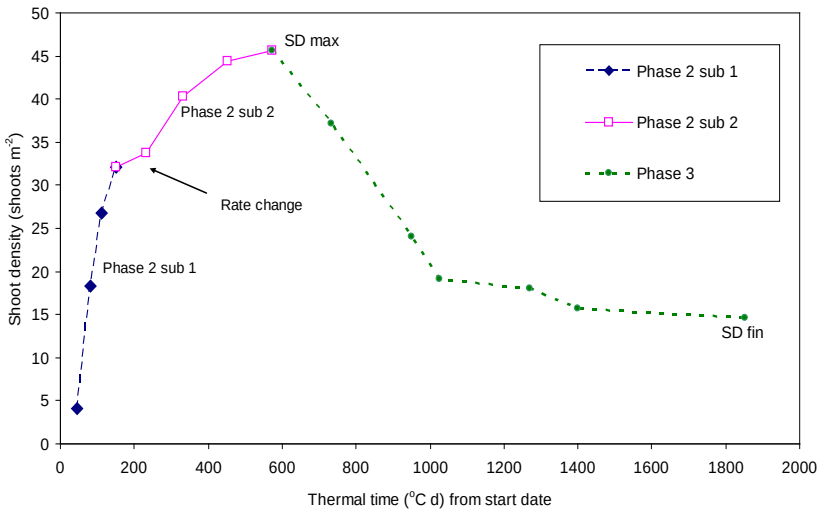


Figure 12 Shoot density in relation to thermal time showing a change in rate of shoot emergence at 150ºC d leading up to peak shoot density of an August NCo376 R3 crop.

shoots were produced in terms of thermal units. The rates of the phase 2 sub 2 of the December crops were taken as thermal time divided by the shoot density at the end of the phase because there were too few points for this starting time. On average, the emergence of NCo376 was quickest during the first sub-phase (in comparison with N25 and N26) and slowest during the second sub-phase of phase 2 of R3 crops (Table 4).

Emergence rate of phase 2 sub 1 was distinctly slowest in April ratoon and quickest in the March and December ratoons. Shoots of the June ratoon crop required three times the amount of thermal units to emerge (°C d shoot $^{-1}$ m^{-2}) than was required during the August ratoon crop. The reason for the markedly slower emergence of shoots during phase 2 sub 2 of all April ratoon crops is not immediately apparent. The ratios between SD at the end of phase 2 sub 1 and final stalk density (SDfin) of shoot emergence of R 3 June, August and December ratoons and in R2 May, August and December ratoons ranged from 1.3 to 2.4. The mean of these ratios are not very different from the 1.62 found by Bezuidenhout *et al*., (2003). It was proposed that this number represents the number of buds on the stubble part of each stalk harvested at the end of the previous

Table 4 Shoot emergence rates (ºC d shoot^{-1}m^{-2}) of sub-phases 1 and 2 of phase 2 of three cultivars started at five times in R3 crops.

Cultivar	Start date R3 crops	Shoot emergence rate (ºC d shoot^{-1}m^{-2})	
		Sub-phase 1	Sub-phase 2
N26	March	6.64	10.33
	April	6.96	41.93
	June	14.14	22.64
	August	3.68	27.89
	December	4.00	17.73
NCo376	March	4.19	23.64
	April	4.53	83.34
	June	6.30	20.66
	August	2.69	20.77
	December	2.14	7.89
N25	March	7.50	9.27
	April	6.29	50.29
	June	7.86	24.07
	August	2.79	25.29
	December	4.57	17.64
Overall means		5.62	26.89
Means Ratoon dates	March	6.11 ± 1.22a	14.42 ± 5.68a
	April	5.92 ± 0.89a	58.52 ± 15.53b
	June	9.43 ± 2.94b	22.46 ± 1.21c
	August	3.05 ± 0.39c	24.65 ± 2.56c
	December	3.57 ± 0.90c	14.4 ± 4.01a
Means Cultivars	N26	7.08 ± 2.11	24.11 ± 5.94
	NCo376	3.97 ± 2.21	31.26 ± 4.61
	N25	5.80 ± 2.25	25.31 ± 13.62

crop (e.g. R2 for R3). As such, these developed as the primary shoots in the R3 crops and appeared over a period of between 150 and 299ºC d (Tb =16°C), depending on starting date. Bezuidenhout (2000) assumed that this phase took 153.4°C d (Tb = 10°C).

3.2.4 Shoot density decline – phase 3

The initiation of the decline in living shoot numbers marks the start of phase 3. Shoots started dying when N25 and NCo376 were intercepting on average about 80% of PAR, however, in comparison N26 was intercepting on average only 58% of PAR (Appendix 2(c)). There was no obvious association between the interception of PAR, which is assumed to be the trigger of shoot senescence, and crop start date. Inman-Bamber (1994b) observed that shoots started dying when the crop was intercepting 70% of PAR and from this it was assumed that there is a threshold PAR level that is needed for shoot survival (Zhou *et al*., 2003). The % PAR interception at the start of shoot senescence varied considerably for cultivars (Zhou *et al*., 2003; Donaldson, Redshaw & Singels,

2003) and crop start date (Donaldson *et al*., 2003). Zhou *et al*., (2003) observed that shoot senescence of low population cultivars started at lower PAR interceptions than high population cultivars and this is confirmed in the present study by the low % PAR intercepted by N26 compared with NCo376 and N25 at the start of shoot senescence. The rate at which shoots died, slowed at about 1200ºC d (Tb 16°C) in NCo376 and N25, and at 2000 °C in N26, particularly in R3 crops (Figure 5). After 1200ºC d, phase 3 was

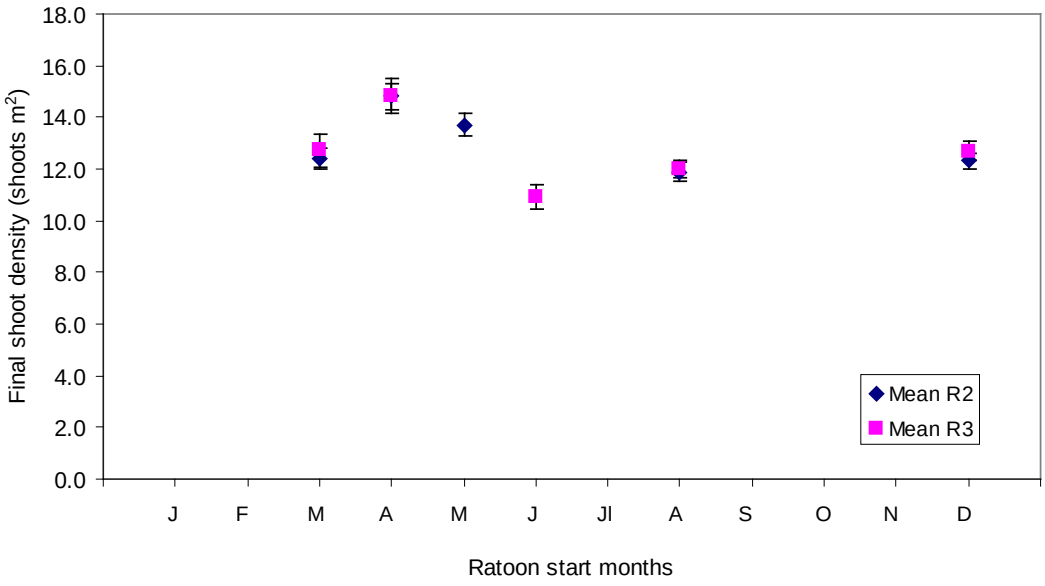


Figure 13 Mean final shoot density of cultivars in each of five starting times of R2 and R3 crops. Bars denote standard errors (P=0.05).

characterised by a slower rate in decline of shoot densities to the final sampling dates. Generally the R2 and R3 March and April ratoons had higher final shoot densities at the age of 12 months than August and December ratoon crops (Figure 13) (see also Figure 9 in Lonsdale and Gosnell, 1976). NCo376 had significantly (P=0.05) SDfin than N26 in R2. April and May ratoons had significantly (P=0.05) higher SDfin than March, August and December ratoon crops. The June ratoon of R3 cycle had the lowest final shoot densities and was significantly (P=0.05) lower than April and May ratoons. The cumulative thermal units between SDmax and when crops were 12 months old in the R3 crops generally increased from 1 830ºC d for the March ratoons to 1 885ºC d for the December ratoons. There appeared to be a linear decline in the mean SDfin of the cultivars N26, NCo376 and N25 with increasing cumulative thermal time between

SDmax and the crop age of 12 months (R^2 =0.5629). Final stalk density per thermal time (SDfin/TT) was strongly correlated (R^2=0.7344) with maximum stalk density (SDmax/TT) of N26 R3 ratoons (Figure 14). There also appeared to be a weak linear association (y = 2.1838x + 106675; R^2 = 0.292, n =30) between the maximum shoot densities attained by NCo376, N25 and N26 crops and their final shoot densities at the age of 12 months within the narrow range of 1800 to 2100°C d. This suggests that 73% of the variation in SDfin can be ascribed to SDmax so that high SDmax will result in high SDfin. However, the range in cumulative thermal time at the time of harvest was narrow and therefore this relationship needs to be tested over a wider range of temperatures.

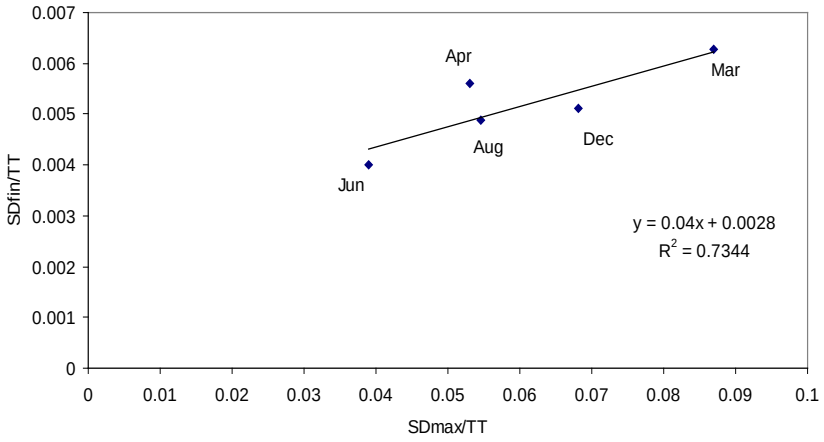


Figure 14 Final shoot densities as a function of cumulative thermal time (SDfin/TT) in relation to maximum shoot density as a function of cumulative thermal time (SDmax/TT) of N26 R3 March, April, June, August and December ratoons when harvested at the age of 12 months.

In Australia, SDmax of plant crops were directly related to the number of primary shoots (bud density in plant material) established after planting. However, there was also a negative relationship between the numbers of primary shoots and the number of secondary shoots per primary shoot that contributed to crop yield (Bell & Garside, 2005). Studying the partitioning of photosynthate to primary and secondary shoots and the role of radiation quality in shoot survival could provide further insights into shoot population dynamics which appear to be different in plant and ratoon crops. Tillering in wheat (*Triticum aestivum* L.) is controlled by the gene *tin*. It is possible that tillering in sugarcane can also be genetically manipulated e.g. by suppressing shoot numbers to improve water use efficiencies and possibly increasing the harvest index (Motozo, Giunta & Deidda, 2004).

3.3 Concluding Discussion

The pre-emergence phase described in this chapter included the period when buds were dormant immediately after harvesting the previous crop as well as the time taken for shoots to elongate to the soil surface. The dormancy from the time the previous crop had been harvested to germination could be due to the suppressing effect of the lingering auxin, produced by apical meristematic tissue of the harvested crop, on the growth of the buds that produce the next crop (van Dillewijn, 1952). The analysis showed that the time to emergence increased from March to June and was less through August to December. The time taken for crops to emerge was largely determined by starting date and was associated with the temperature of the pre-emergence period (Hay & Walker, 1989). This was confirmed by strong associations between the mean temperatures during the pre-emergence period and the time taken by shoots of NCo376, N25 and N26 to emerge. A simple comparison showed that soil temperature was no better than air temperature as a predictor of the time taken for shoots to emerge when all surface plant residues from the previous crop had been cleared away. McMaster & Wilhem (1998) also found no gain from using soil temperatures to predict early development of wheat. This is fortuitous since soil temperatures are not presently standard measurements in automated weather stations. Keating, Robertson, Muchow & Huth (1999) have assumed that germination required 100ºC d (Tb = 9ºC) and thereafter shoots elongated to the soil surface at the rate of 0.8 mm per ºC d. The base temperatures estimated in this study (10.8°C to 12.9°C), using the formula of Yang *et al*., (1995) for the pre-emergence phase, were similar to the 12ºC given by Barnes (1974) and 11.6 and 11.8ºC by Liu *et al*., (1998) for germination of sugarcane. It is acknowledged that the time at which shoots emerged may need to be determined with more accuracy than was done in this study. However, for the present, the analyses of NCo376, N25 and N26 showed that for the pre-emergence phase the base temperatures were 12.7, 12.4 and 10.8ºC, respectively. The cumulative thermal times required for germination in NCo376 and N25 were 94.4 $\pm$ 6.05 and 97.8 $\pm$ 16.32 °C d (base 12.7 and 12.4 °C, respectively) and 115.2 $\pm$ 10.45 °C d for N26 (base 10.8ºC).

The maximum shoot density varied substantially among the cultivars and this was similar to the data presented in a study by Zhou *et al*., (2003). In the present study NCo376 consistently had the highest SDmax (up to 63 m^{-2}) . The lowest shoot densities were consistently recorded in N26 which is commonly regarded to be a low shoot densities

cultivar. The attainment of SDmax by NCo376, N25 and N26 was, however, modified by the climatic conditions during the emergence period leading up to SDmax. This was probably mediated by the interaction of changing radiation quality and the accumulation of growth regulating hormones. Low temperatures favoured accumulation of auxin in shoots of Tall fescue (*Festuca arundinacea* Schreb.) which was associated with rapid tiller development (Yeh, Matches & Larson, 1976). There was agreement between SDmax developed for each starting time and shoot appearance rates during the first sub-phase i.e. high appearance rates lead to high SDmax. Shoots took longer to appear in winter crops and appeared much quicker in spring and summer starts. Crops started in autumn developed lower SDmax, especially in N26. SDmax was higher in crops started after winter. It is possible that this seasonal effect was the cause of the systematic deviation in the polynomial model presented by Inman-Bamber (1994b). The period of shoot emergence to SDmax across cultivars and starting months differed widely in terms of Julian days. Cultivars differed most in SDmax in crops started in December but the mean time to shoot emergence of the cultivars for each of the two cycles (R2 and R3) were similar.

The data presented have only considered PAR as the trigger for the onset of shoot senescence. High tillering rates in barley were associated with high levels of intercepted radiation (Abeledo, Calderini & Slafer, 2004). In the present study interception of PAR varied between 41 % and 100% at the start of shoot senescence, depending on crop start date and cultivar. This was evidence that the trigger that determines shoot senescence may not be solely the amount of PAR reaching a shoot but that production and survival of shoots are also related to shifts in quality of filtered radiation, specifically R:FR (Casal, Deregibus & Sánchez, 1985; Sparkes *et al*., 2006) and possibly green radiation (Folta & Maruhnich, 2007). The decline in shoot numbers was however shown to be correlated to temperature and this suggested that mature shoots could die at a more rapid rate in crops harvested in summer months. Loss of mature stalks late in the development of a crop could have a significant impact on yields.

CHAPTER 4

LEAF AND LEAF AREA DEVELOPMENT

4.1 Introduction

There are few data that relate shoot density and leaf development to canopy development in cultivars other than NCo376 in South Africa. In particular little is known about the effect of crop start date on canopy development. The objective in this chapter is to provide some detail of the rate of leaf appearance, leaf size and the rate of senescence with particular reference to cultivar differences and to crop starting dates. The aim was to describe how leaf development, together with shoot development, forms a canopy. The interception of radiation by the green canopy is described in Chapter 5.

4.2 Results and Discussion

4.2.1 Mass and size of leaves on early emergent shoots

An emerging shoot is initially composed of several bracts (up to eight) (Van Dilliwjin, 1952) before leaves can be defined. The leaves on the earliest shoots that had emerged at the time of sampling were measured and they are therefore assumed to be characteristic of primary shoots of a ratooning crop. The derived rates at which these leaves were produced are described in section 4.2.2 below. Leaf lamina areas were more variable in N26 than in N25 and NCo376 of the samples taken in the April crop (Figure 15). Leaf lamina area increased linearly in relation to the sequence in which they

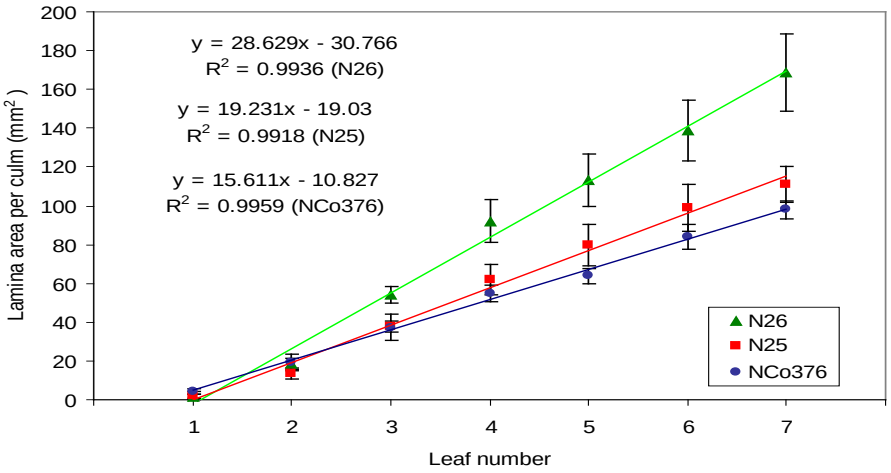


Figure 15 Leaf lamina areas of the first seven leaves on shoots of the sugarcane cultivars NCo376, N25 and N26 of crops started in April. Leaf numbering counted in sequence of appearance (i.e. from the culm base upwards). Bars denote standard errors.

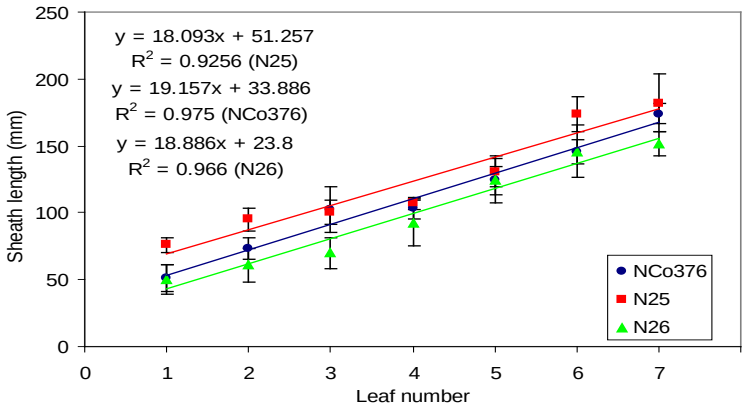


Figure 16 Leaf sheath lengths of the first leaves of NCo376, N25 and N26 crops started in April. Bars denote standard errors (P=0.05).

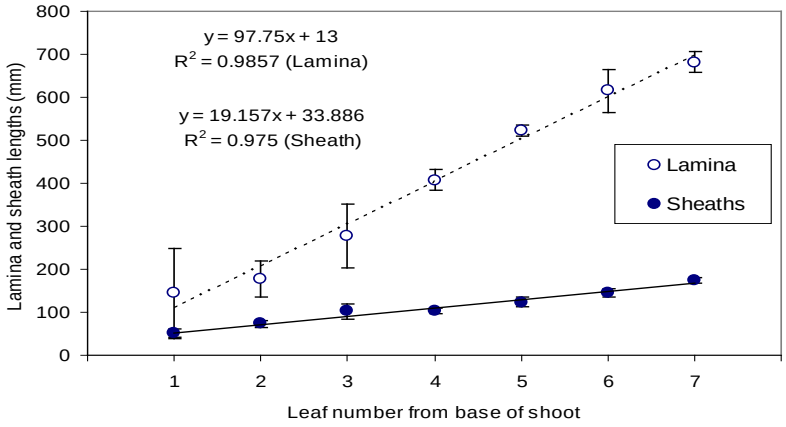


Figure 17 Leaf lamina and sheath lengths of the first seven leaves of the sugarcane cultivar NCo376 started in April. Bars denote standard errors.

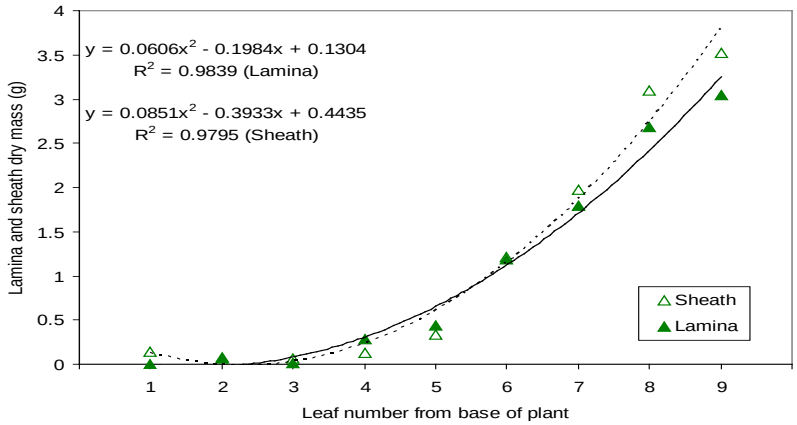


Figure 18 Leaf lamina and leaf sheath dry mass of the first nine leaves of the cultivar N26 of an April ratoon.

appeared. N26 had significantly (P=0.05) the larger laminas than N25 and NCo376 (Figures 15). The increases in lamina lengths were greater than sheath lengths (Figure 16) and both lamina and sheath lengths increased linearly in sequence of leaf appearance. The ratio of lamina to sheath lengths derived from the data presented was 5.1 (Figure 17).

Leaf laminas were increasingly longer than sheaths (Figures 17), however, despite this, the dry mass of these two components of the leaf was similar up to leaf 7 in N26 (Figures 18). Sheaths were heavier than laminas from leaf 7 onwards and were 13.6% heavier than laminas at leaf number 9. Leaf lamina areas were larger with successive leaf numbers up to a maximum size after which they either remained the same size or decreased in size (Figure 23). N25 had the largest laminas after which N26 laminas were largest (Figures 15 and 19). The average maximum lamina areas of the March ratoon were 423 $\pm$ 17.4, 411 $\pm$ 7.5 and 315 $\pm$ 37.1 cm² for N25, N26 and NCo376, respectively. Maximum lamina areas were attained at leaf 13 by N26 and at leaf numbers 17 and 18 by NCo376 and N25. Maximum lamina lengths were 1454 $\pm$ 83.3, 1334 $\pm$ 52.3 and 1235 $\pm$ 36.8 mm for N25, NCo376 and N26, respectively (Figures 19). N26 had the widest leaf laminas, reaching a maximum width of 54.3 $\pm$ 1.43 mm which was attained at leaf number 13 (P=0.05) (Figure 19 of a March ratoon) after which the lamina width remained relatively constant. Laminas of N25 and NCo376 reached their maximum width at leaves 18 and 17, attaining widths of 44.2 $\pm$ 1.26 and 37.1 $\pm$ 2.06 mm, respectively. The relationship between the product of length (Ln) and width (W) divided by area (A) is referred to as the shape factor (f) (Sinclair, Gilbert, Perdomo, Shine, Powell & Montes, 2005). When only Ln and W are measured, A can be derived by Ln x W x f. The factor for each of the cultivars was determined by measuring Ln, W and A of 70 laminas. The factors thus derived were 7.0 $\pm$ 0.019 (n=70), 6.9 $\pm$ 0.009 (n=73), and 6.7 $\pm$ 0.018 (n=74) for NCo376, N25 and N26, respectively. These factors were used on occasions when the apparatus used to measure lamina area failed and only Ln and W were measured. Ratoon date had a distinct effect on lamina areas of primary shoots of N26. In August and December ratoons laminas of low leaf numbers of primary shoots were significantly (P=0.05) larger than in March ratoons (Figure 20). After leaf number 10 and up to 18, laminas of August ratoon crops were significantly (P=0.05) larger than laminas of March and December ratoon crops.

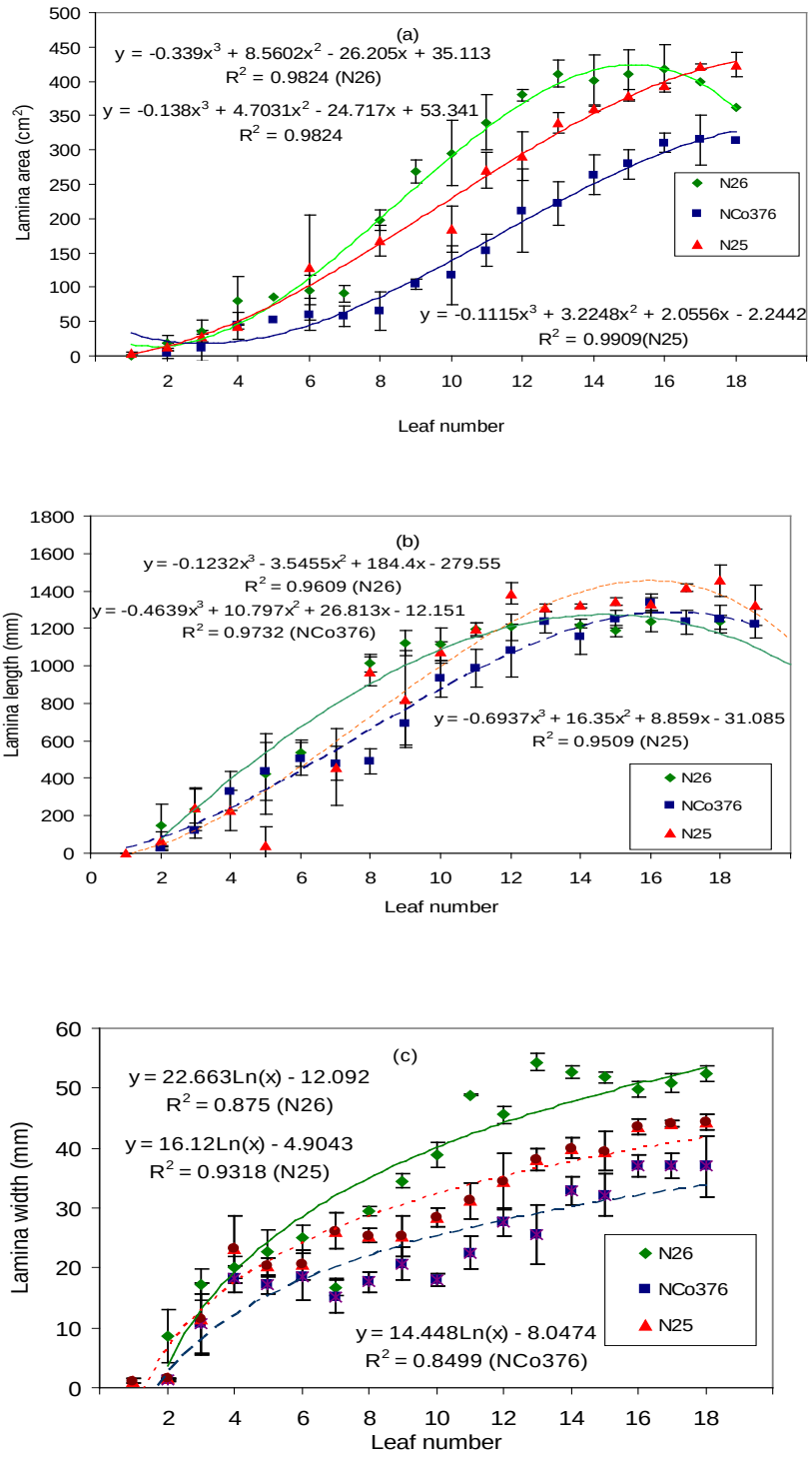


Figure 19 Lamina (a) areas, (b) lengths and (c) width of N26, NCo376 and N25 of leaves from March ratoon crops. Bars denote standard errors (P=0.05).

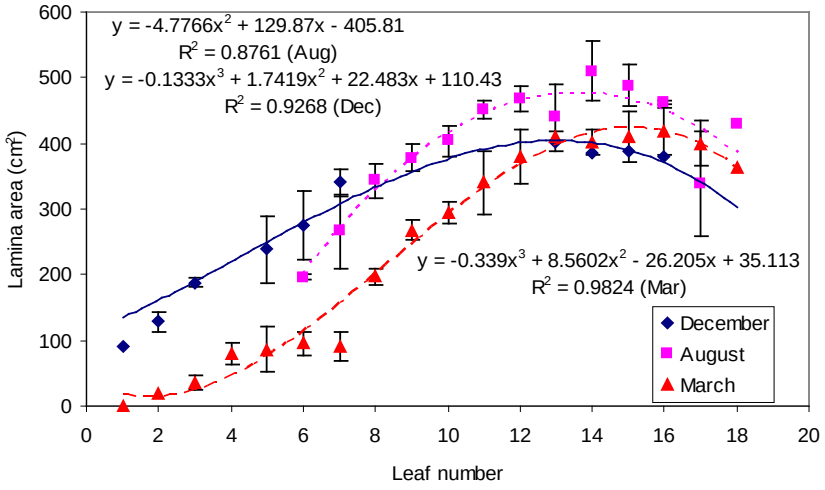


Figure 20 Lamina areas of primary shoots of N26 of March, August and December ratoons. Bars denote standard errors (P=0.05).

4.2.2 Appearance rates of leaves on early emergent shoots

Bonnett (1998) suggested that a power-law function described the continually changing phyllochrons with leaf number, particularly when considering the appearance of more than 30 leaves per stalk. Zhou *et al*. (2003) have also suggested that a biphasic linear model did not describe the increasing phyllochron intervals with successive leaves of several cultivars, including NCo376. However, it was apparent that the first 12 leaves were produced at a faster rate than later leaves. The biphasic linear description (Inman-Bamber, 1994b) of leaf appearance rates was considered to be the most appropriate model to apply to the data in order to assess seasonal affects on phyllochrons (Figure 21). The point at which the rate of leaf appearance changed was determined by iteration of the linear regressions of the plotted data to determine the highest R^2 values for the first phllochrons. By this process the change in rate was determined to have occurred between leaf numbers 12 and 13 when leaf appearance was plotted against thermal time (Tb 10°C) (Figure 21). Linear functions fitted to the first 12 leaves gave better R^2 values than power functions. The phyllochrons of the first leaves, phyllochron 1, thus determined from the appearance of the first leaves (rather than crop start date) in the five starting times (Table 5) for NCo376, N25 and N26 were 99.1, 88.9 and 93.7°C d, respectively. Mean phyllochron 2 (leaves 13 upwards), similarly determined were 177.1, 173.8 and 176.1°C d, for NCo376, N25 and N26, respectively. Thus there was greater

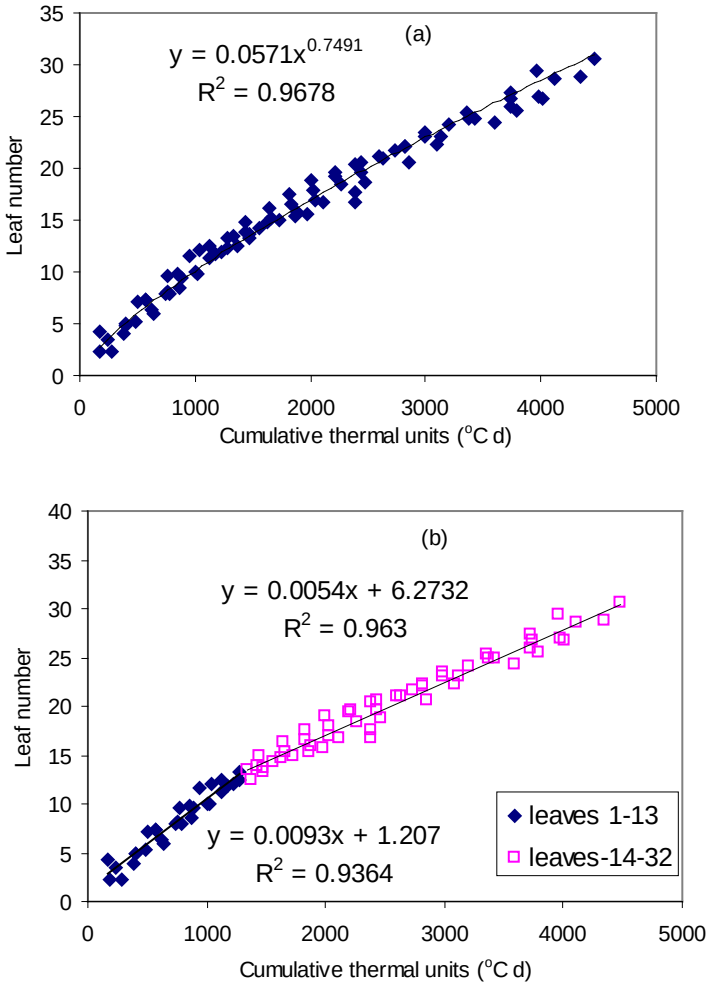


Figure 21 Leaf number production in relation to cumulative thermal time (Tb 10°C) for the sugarcane cultivar N25 for March, April, May, August and December ratoons described by (a) power-law function and (b) by two fitted linear functions.

variation between cultivars with respect to rate at which leaves 1 to 12 appeared than the appearance of later leaves. The mean pyllochron 1 intervals determined for each of the ratoon months was longer in March, April and May (94.5 - 90.7°C d) than in the August ratoon (80.4°C d) and was longest in the December ratoon (109.5°C d) (Table 5). Differences between the three cultivars were most evident in the May ratoons when the rate of appearance of N25 leaves (75.2°C d) was much quicker than those of both NCo376 (97.1°C d) and N26 (100.0°C d). The trend seen in the phyllochron 2 intervals depicted in relation to the months in which their first leaves appeared, instead of crop

start date, suggests that phyllochrons are modified by some factor like changing radiation environments (Table 5).

Table 5 Phyllochrons 1 and 2 (°C d) for the sugarcane cultivars, NCo376, N25 and N26 of five crop starting dates.

Phyllocron 1						
Start month	March	April	May	August	December	Mean ± SD
NCo376	97.1	102	97.1	85.5	113.6	99.1 ± 10.14
N25	88.5	89.3	75.2	79.4	107.5	88.9 ± 12.45
N26	98.0	86.9	100.0	76.3	107.5	93.7 ± 12.22
Mean	94.5	92.7	90.7	80.4	109.5	93.9
SD	±5.24	±8.11	±13.56	±4.68	±3.52	± 7.02
Phyllocron 2						
NCo376	153.8	172.4	188.7	185.2	185.2	177.1 ± 14.41
N25	163.9	172.4	172.4	181.8	178.6	173.8 ± 6.87
N26	151.5	169.5	181.8	192.3	185.2	176.1 ± 16.03
Mean	156.4	171.4	180.9	186.4	183	175.7
SD	± 6.60	± 1.67	± 8.18	±5.36	± 3.81	± 12.11

4.2.3 Average leaf sizes

There were relatively large variations in leaf size for a specific leaf number (Figure 22). The trend of increasing leaf lamina area with leaf number up to a maximum of the primary shoots in the April ratoon is similar to that described for primary shoots by

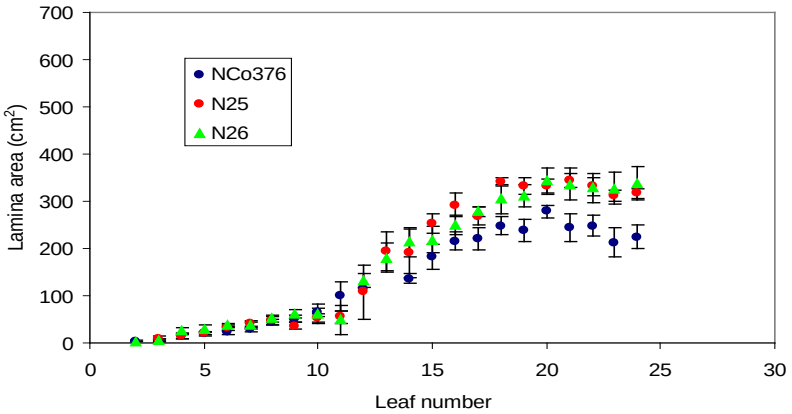


Figure 22 Leaf lamina areas of primary shoots of NCo376, N26 and N25 April ratoon crops. Bars denote standard errors (P=0.05).

Singels *et al.* (2005b). When primary and secondary shoots were combined and analysed collectively the leaf number, or position on the stalk, at which the largest leaf

was first reached tended to be higher in March, April and May ratoons than in August and December ratoons. The leaf numbers, at which maximum lamina size was attained, also varied amongst the cultivars (Table 6). For the March, April and May

Table 6 Maximum lamina area (cm^2) and leaf number when it was first reached of NCo376, N25 and N26 in March, April, May, August and December ratoons.

Start month	March		April		May		August		December		Mean ±SE	
Cultivar	Leaf No.	Leaf size	Leaf No.	Leaf size	Leaf No.	Leaf size	Leaf No.	Leaf size	Leaf No.	Leaf size	Leaf No.	Leaf size
NCo376	16	424	20	278	14	310	12	353	13	401	15.0 ± 1.6	353.2 ± 60.8
N25	21	286	21	344	20	344	12	315	12	361	17.2 ± 2.4	330.0 ± 29.6
N26	13	435	15	501	20	475	14	510	13	596	15.0 ± 1.5	503.4 ± 59.4
Mean	16.6	381.6	18.6	374.3	18.0	376.3	12.7	392.7	12.7	452.7	15.7	395.5
±SE	2.9	58.9	2.3	81.2	2.5	61.8	0.8	73.3	0.4	89.2	1.4	32.7

ratoons the leaf numbers were 20-21 for N25, 14-20 for NCo376 and 13-20 for N26, respectively. For the August and December ratoons the leaf numbers at which maximum leaf sizes were attained were 12-14 when all three cultivars were considered (Figure 23). This suggests that maximum leaf size is reached at a higher leaf number in March, April and May ratoons than in August and December ratoons. Both N25 and N26 had the largest leaves in the December ratoons and the smallest leaves in the March ratoons. For the cultivar NCo376 leaves were largest in the March ratoon and smallest in the April ratoon. On average leaf sizes were not significantly different but the largest leaf size was reached at a significantly (P=0.05) lower leaf number in August and December ratoons than in March, April and May ratoon crops (Table 6). Leaves on secondary shoots of NCo376 were shown to be larger than leaves on primary shoots of a crop planted in November (Singels *et al*., 2005b). The leaf lamina areas derived from the mean of shoots in samples taken at several sampling dates were compared with leaf lamina area profiles of early emergent shoots, designated as primary shoots (Figures 19 and 20) in Figure 24. Leaf lamina areas of primary shoots were smaller (and slower to reach maximum size) than the mean lamina areas of leaf numbers up to and greater than 20 of NCo376, up to leaf number 16 of N26 and up to leaf number 12 of N25. It is possible that in sugarcane higher order shoots (tillers) appear in increasingly shadier environments in which the far-red component of radiation increases in relation to the red component of

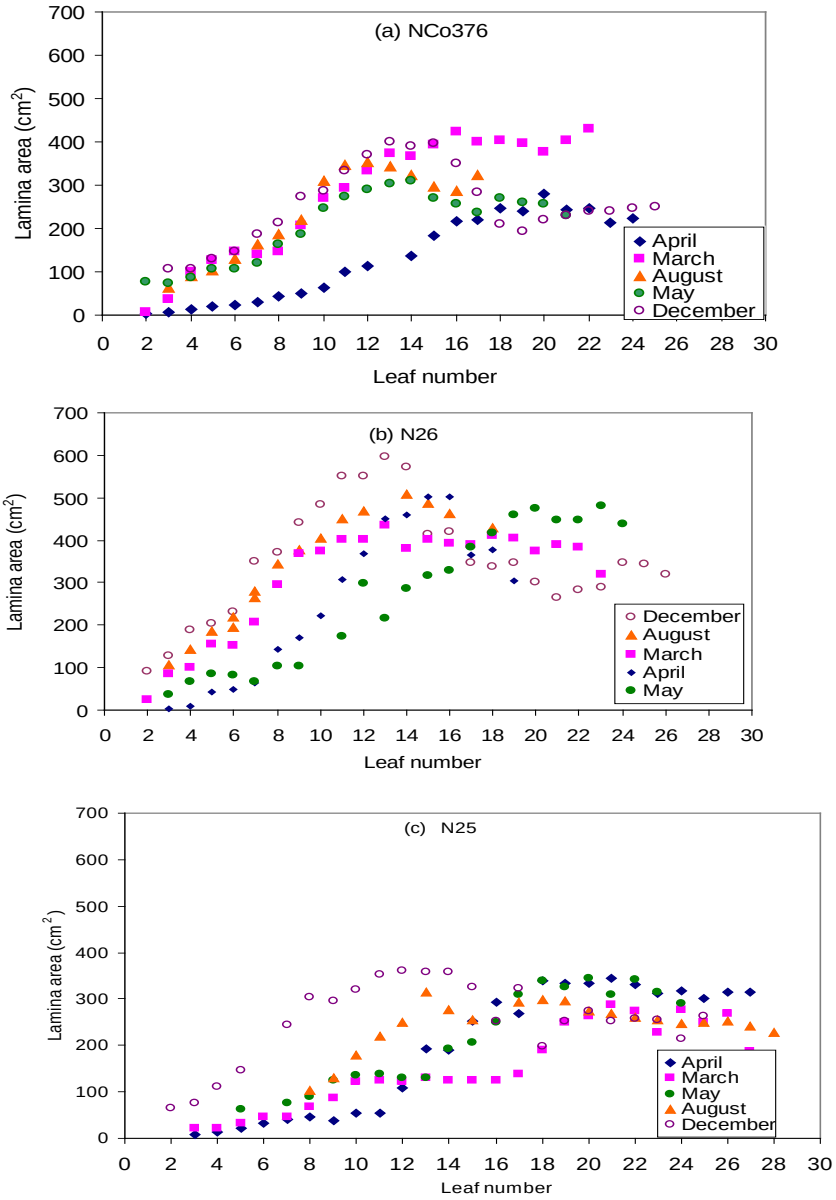


Figure 23 Mean areas of lamina from (a) NCo376, (b) N26 and (c) N25 of March, April, May, August and December ratoons.

light. Skinner & Simmons (1993) showed that supplemental far-red radiation increased leaf length of spring barley without increasing the time taken to produce a leaf. However, secondary shoots may initially elongate at a faster rate than primary shoots (this was not measured) so that leaves produced later by primary and secondary shoots may have developed in similar radiation environments and consequently differences in leaf sizes were less marked, as was evident in N25 and N26 (Figure 24). Higher order shoots that

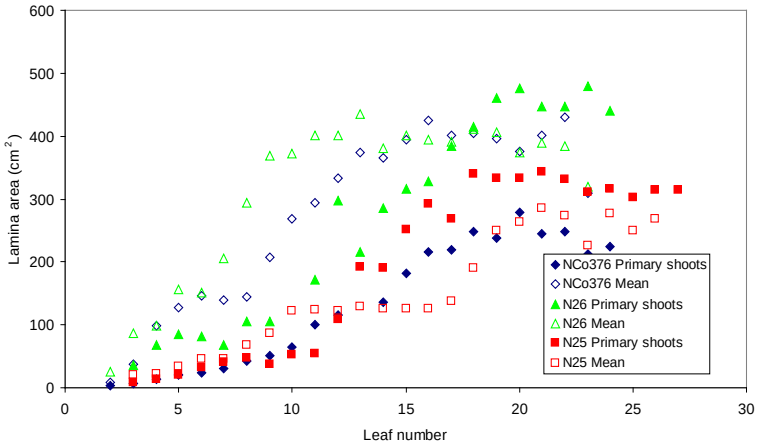


Figure 24 Mean lamina areas (closed symbols) and of the primary shoots (open symbols) of NCo376, N26 and N25 sugarcane cultivars which commenced growth in March.

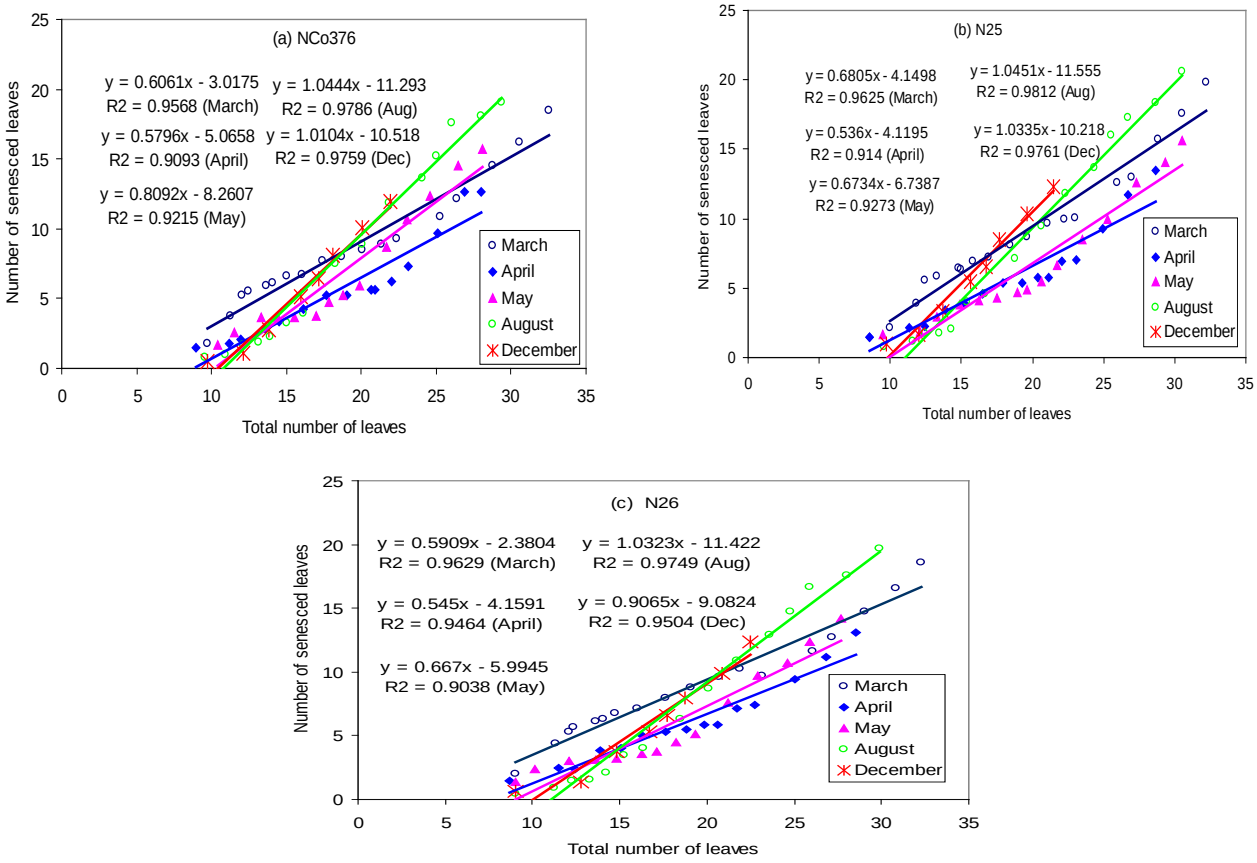


Figure 25 Number of senesced leaves in relation to total number of leaves of sugarcane cultivars NCo376 (a), N25 (b) and N26 (c) from crops started at in five different months. Linear functions are in graphs and Appendix 3.

do not elongate sufficiently to compete with shoots that had emerged earlier are more likely to succumb to the lack of sustainable radiation penetrating through the developing canopy. The larger leaves of the higher order shoots would then no longer contribute to the mean leaf lamina area value, thus stabilising or reducing the mean lamina area value at higher leaf numbers.

4.2.4 Leaf senescence

Leaf senescence started after eight leaves had been produced in the March and December crops, after six leaves in the April and May crops and after seven leaves in the August crops. This is similar to the number stated by Robertson *et al*. (1998) who found that leaf senescence started after seven leaves had appeared. The number of senesced leaves is highly correlated with the total number of leaves on a stalk (Inman-Bamber, 1994b and Robertson *et al*., 1998). Once senescence had started the rate was 0.91 senesced leaves per fully expanded leaf in Robertson's' study (Robertson *et al.,* 1998) and 0.98 for NCo376 and 0.97 for N12 according to Inman-Bamber (1994b). The regression of senesced leaves on number of emerged leaves (Figure 25 and Table 7)

Table 7 Rates of leaf senescence as a function of total number of leaves per shoot and as a function of thermal time of NCo376, N25 and N26 for March, April, May, August and December ratoons in relation to the month in which the 10th leaf appeared.

Crop start date	Leaves senesced per total leaves			Leaves senesced per 100°C d		
	NCo376	N25	N26	NCo376	N25	N26
Mar	0.61	0.68	0.59	0.51	0.55	0.51
Apr	0.58	0.54	0.55	0.39	0.37	0.36
May	0.81	0.67	0.67	0.46	0.42	0.41
Aug	1.04	1.04	1.03	0.61	0.63	0.60
Dec	1.01	1.03	0.91	0.68	0.66	0.65

starting from the leaf number when senescence started suggests that season has a significant effect of the rate of leaf senescence. Senescence rates were slower in March and April than in May ratoons and were highest in August and December ratoons (Figures 25, 26 and 27) when plotted against the month of year in which the 10th leaf appeared. The10th leaves appeared in May, July, October and February of March, April, August and December ratoons, respectively, for all three cultivars. The 10th leaf of the

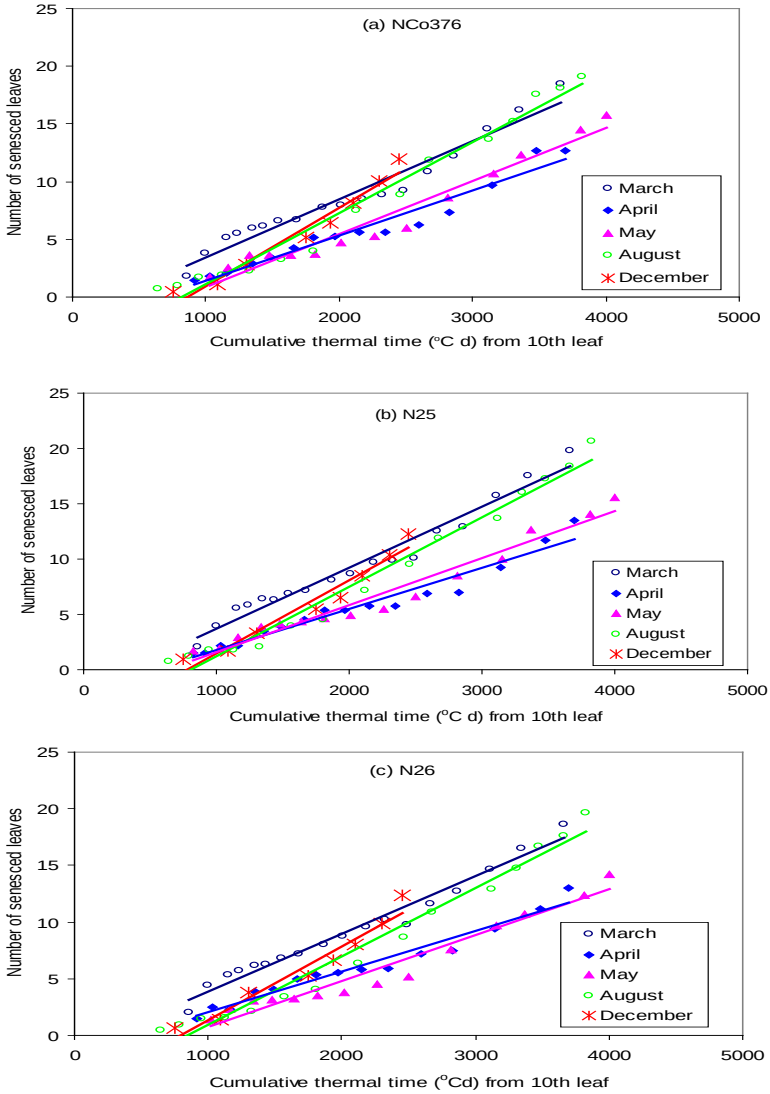


Figure 26 Number of senesced leaves in relation to thermal time calculated from the time of the appearance of the 10th leaf of (a) NCo376, (b) N25 and (c) N26 March, April, May, August and December ratoons. Linear equations are in Appendix 3.

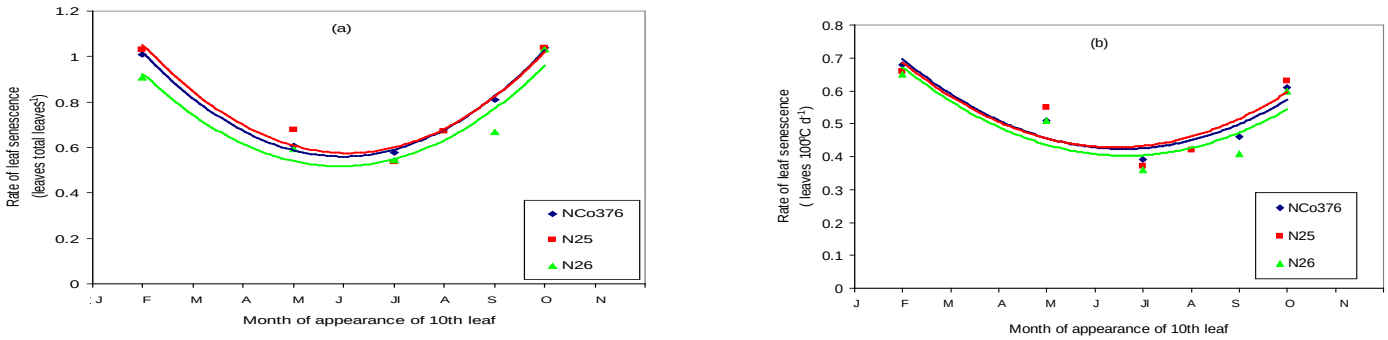


Figure 27 Rate of leaf senescence of the sugarcane cultivars NCo376, N25 and N26 expressed in terms of (a) senesced leaves per total number of leaves present and (b) leaves senesced during intervals of 100°C d heat units calculated from the month in which the 10th leaf appeared from crops started in March, April, May, August and December.

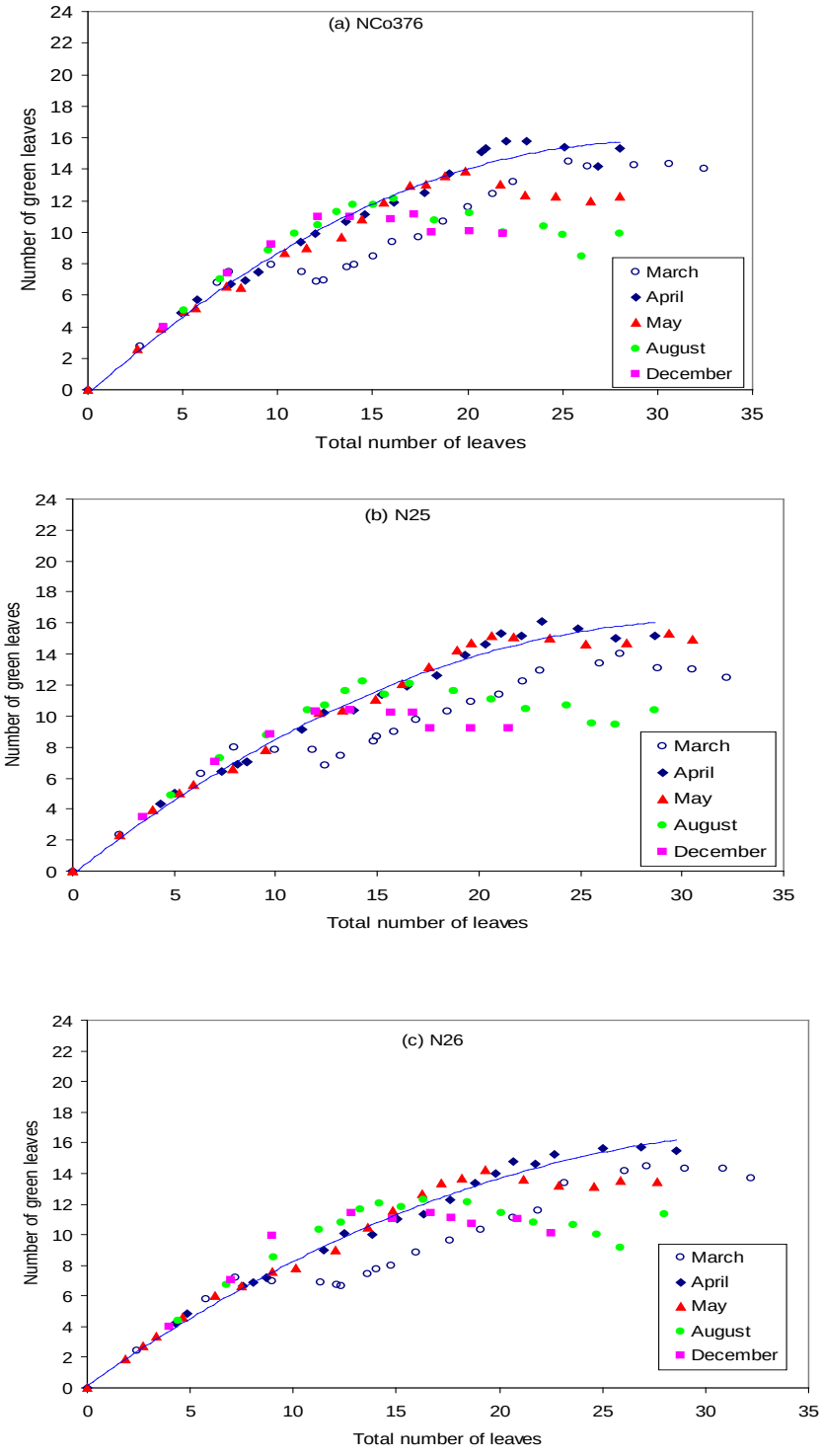


Figure 28 Number of green leaves per stalk of (a) NCo376, (b) N25 and (c) N26 crops started in March, April, May, August and December. Polynomials fitted to April crops are (a) $y = -0.0179x^2 + 1.0737x - 0.286$ ($R^2 = 0.9808$), (b) $y = -0.0163x^2 + 1.0326x - 0.2037$ ($R^2 = 0.9856$), (c) $y = -0.0134x^2 + 0.9444x + 0.1564$ ($R^2=0.9913$).

May ratoon crops appeared in August for N25 and in September for N26 and NCo376. The rates of senescence were higher in the August and December ratoons and lower in the March, April and May ratoon crops than those quoted for a single crop start date by Robertson *et al.* (1998) and Inman-Bamber (1994b) (Table 7).

The regressions of leaf senescence against cumulative thermal time (Figure 26) similarly showed lower rates for March, April and May ratoons (Table 7, Figure 26) and higher in August and December ratoons. The general trends suggest that senescence rates were similar in NCo376 and N25 and that the rate was generally lower in N26 (Figure 26). Not withstanding the trends, values show that rates were higher in NCo376 than in N25 and N26 in the April and May ratoons (Table 7). For example, NCo376 leaves of May ratoons senesced at a rate of 0.81 leaves for every new leaf produced while the rate was 0.67 for N25 and N26. In terms of thermal units this was the equivalent of 0.46 leaves senescing per 100°C d. On all occasions leaf senescence was slowest in N26. Linear equations describing rates of leaf senescence in Table 7 are listed (Appendix 3).

4.2.5 Green leaf numbers per shoot

The number of green leaves on a stalk is the balance between the rates at which new leaves are produced (described by phyllochrons) and the rates at which older leaves senesce. The results of these two processes are depicted in Figure 28. Green leaf numbers for all crop start dates were similar until leaf senescence started. The March ratoon crops deviated first from the general trend set by the April ratoon crops when green leaf numbers declined due to both a slower leaf production and a higher rate of leaf senescence than in the April ratoon crop. Leaf senescence in March and April ratoon crops was substantially slower than in the other ratoon dates (Table 7). In the December ratoon green leaf numbers started to deviate from the April trend and was lower when there were about 16 leaves were present on the stalk. This was due to the substantially higher rate at which leaves were senescing and the slower rate at which leaves were being produced by the December ratoon, compared with the April ratoon, crops. This was similar in the August ratoon crops and the later deviation could be attributed to the slow rate at which later leaves (phyllochron 2) were produced for this ratoon. After about 20 leaves had been produced, green leaf numbers in May ratoon crops of N25 remained similar to April ratoons, but were lower in the May ratoons of NCo376 and N26. The rate of leaf production was similar in April and May ratoon crops

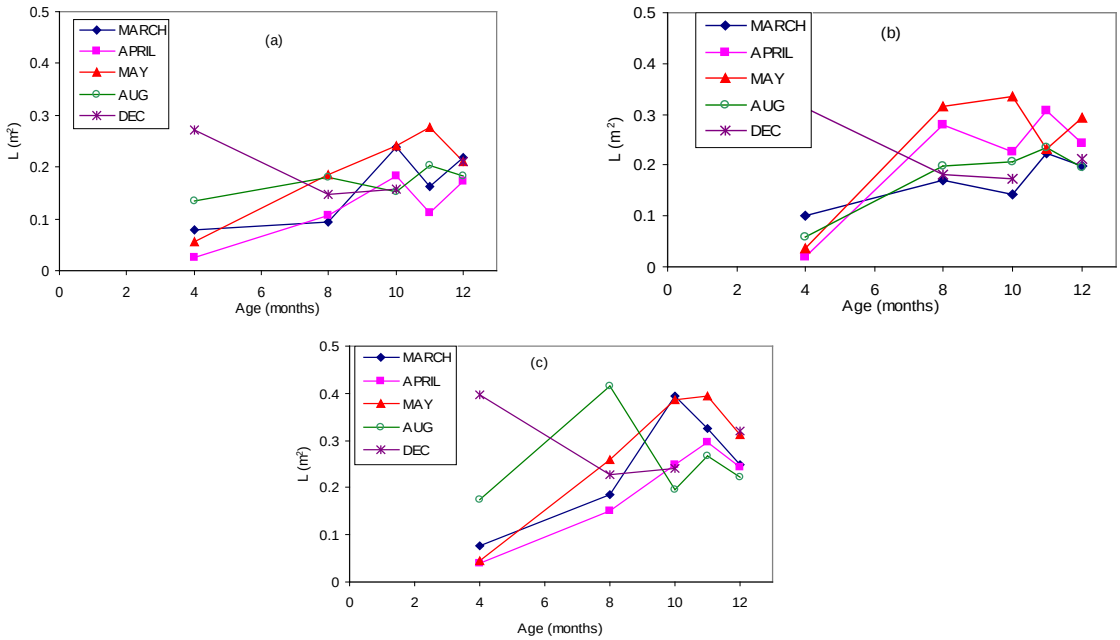


Figure 29 Effect of age on the development of green leaf area (L) per shoot of sugarcane cultivars (a) NCo376, (b) N25 and (c) N26 in crops started in March, April, May, August and December.

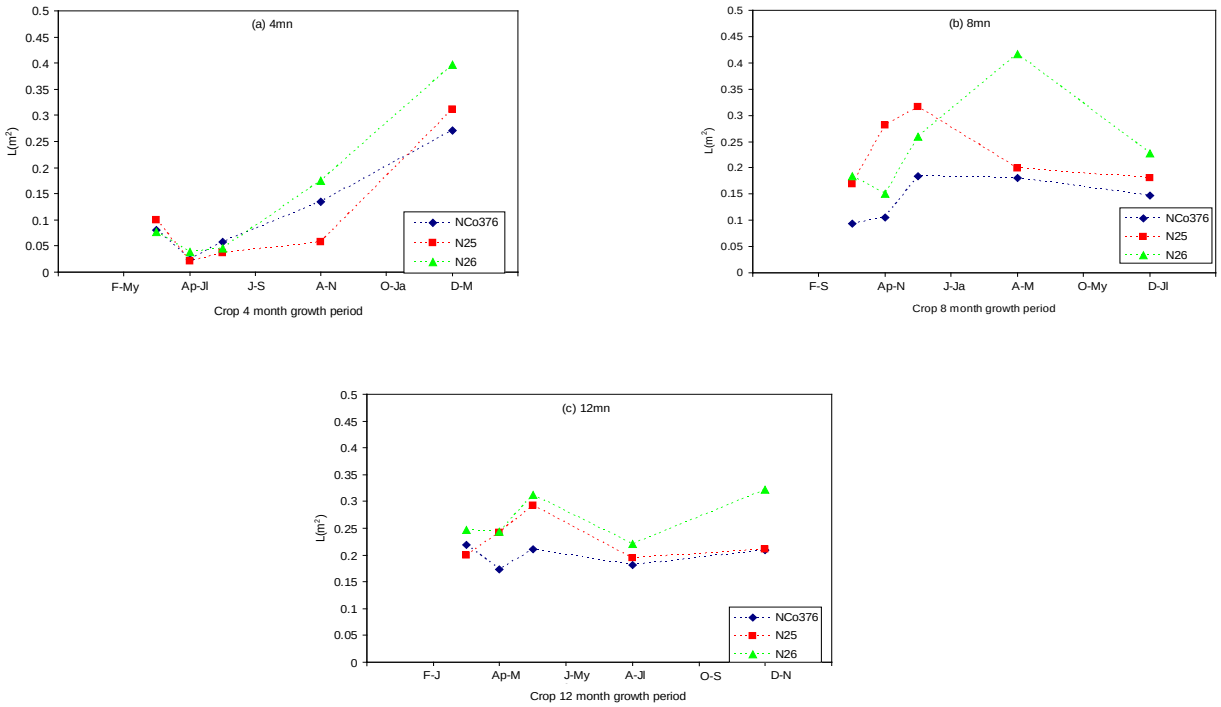


Figure 30 Effect of start date on green leaf area (L) per shoot of sugarcane cultivars NCo376, N25 and N26 in relation to crops started in March, April, May, August and December at the ages of (a) 4 months, (b) 8 months and (c) 12 months.

of N25 and the small deviation in green leaf number was due to a slightly higher rate of leaf senescence. Leaf production in later stages (phyllochron 2) of May ratoon crops of NCo376 and N26 was slower than in April ratoon crops and leaf senescence was higher so that green leaf numbers were lower than in April ratoon crops.

4.2.6 Green leaf area per shoot (L)

At any particular time L is a function of the number and size of green leaves on a stalk. The L of NCo376 generally remained below 0.30 m², while N25 attained levels slightly higher than 0.30 m² in the December and May ratoon crops and N26 crops generally had higher L than 0.30 m² (Figures 29 and 30). Higher L had developed at the age of 4 months in all the cultivars of the December ratoon crops (0.28 to 0.4 m²) compared to other ratoon dates (>0.1 m²) and after 4 months L decreased in the December ratoons. This trend was different in the March, April and August ratoon crops which attained peak L between ages of 10 and 11 months. The L of the N26 August ratoon was only 50% of the area of the December ratoon after 4 months of growth, but L continued to increase and peaked at 0.42 m² at 8 months and then declined to about 0.20 m² at the age of 10 months. Then L fluctuated slightly up to the age of 12 months. In contrast, the L in the August ratoon crop of N25 was very low (about 0.05 m²) at the age of 4 months and increased linearly to about 0.22 m² at 11 months and then declined slightly to the age of 12 months. The L of the NCo376 August ratoon crop was similar to that of N26 at the age of 4 months but thereafter increased gradually to about only 0.20 m² when it was 12 months old. The December ratoons were characterised by very high L when they were 4 months old (0.28 - 0.32 m² in NCo376 and N25 and about 0.40 m² in N26) during a period when radiant flux and temperatures were high. After the age of 4 months L decreased in the December ratoon crop and at 8 months of age during winter, was only about 50% of the L when they were 4 months old. Between the ages of 8 and 10 months L was unchanged in the December ratoon crops. No data were produced at age of 11 months in December ratoon crops because lodging prevented access to the plots and there appeared to be a slight increase in L at the age of 12 months.

4.3 Concluding Discussion

Leaf lamina size increased in sequence of appearance up the culm until a maximum size was attained. Leaves were then the same size or were smaller, depending on the climatic factors that were prevailing at the time the leaves appeared. For example,

lamina size increased up to the emergence of leaf number 13 in the December ratoon crops and leaves appearing after leaf 13 were smaller because they emerged during days when temperatures were lower and daylength (Appendix 6) was declining. In contrast, leaves in crops started in April and May were smaller (emerged when temperatures were lower and daylengths were shorter) and only reached maximum size (smaller than the December ratoon crop) after the emergence of leaf number 18. Leaves that emerged after leaf number 18 were close to the maximum size because they were formed when temperatures were higher and daylengths were longer. Singels *et al*. (2005b) suggested that the size of emerging leaves (sink leaves) is determined by the size of the fully emerged leaves on a culm (source leaves) as well as the temperature and radiation prevailing when the sink leaves emerge, i.e. the larger the area of existing leaves (source) the more photo-assimilate is produced resulting in progressively larger new leaves being formed (sink). This may explain why leaves in March, April and May ratoon crops were generally smaller and reached maximum size after the emergence of a larger number of leaves than in the August and December ratoon crops. N26 had the largest leaves and NCo376 produced larger leaves than N25 specifically in March, August and December ratoon crops, when leaves were emerging in higher temperature than in the April and May ratoon crops. Leaves on secondary shoots (tillers) of NCo376 and N25 were larger than those of the primary shoot. This supports the observation made by Singels *et al*. (2005b) that leaves became progressively larger as shoot order increased. Supplemental illumination with far-red radiation reduced tillering and increased leaf length in spring barley (*Hordeum vulgare* L.) (Skinner & Simmons, 1993). It is therefore very probable that the larger leaves of higher order shoots are a response to changing radiation quality (lower R:FR ratio) in shady environments. The responsiveness of sugarcane to changing daylength was demonstrated by Edwards & Paxton (1979) when they showed that leaf sheaths of flowering sugarcane stalks elongated more rapidly when daylength was declining than when it was held constant at 12.5 hours.

Leaf appearance rate changed perceptibly after the appearance of the 12th leaf so that two linear equations (phyllochrons 1 and 2) were used to describe leaf appearance rates. Phyllchron 1 was calculated to be 99.1, 88.9 and 93.7°C d and phyllochron 2 was calculated to be 177.1, 173.8 and 176.1°C d for the cultivars NCo376, N25 and N26, respectively. Sinclair, Gilbert, Perdomo, Shine, Powell & Montes (2004) argued that air

temperatures measured in the meteorological station were higher than air temperature in a developing sugarcane canopy and this could have resulted in an estimated decrease in leaf appearance rate when it was expressed as a function of cumulative thermal units. The change in the rate of leaf appearance has been associated with a higher demand of photosynthate when root development enters a fast growing phase (Van Antwerpen, 1999). The data presented earlier in this chapter suggest that the development of the first 12 leaves was under the influence of soil temperature and then when the culm emerged above soil level leaf development was under the influence of air temperature. The switch in leaf appearance rate may also have been associated with a greater demand in photosynthate by the culm as it started to elongate rapidly. Phyllochrons were affected by season, shortening as temperatures declined from May to August crop start dates; and lengthened as temperatures and daylength rose from the August to the December crop start (Appendix 6). Phyllonchron 2 responded sooner to increasing temperatures and daylength than phyllochron 1. These trends suggest that leaves required less photo-assimilate to appear in winter than in summer because leaves produced in winter were smaller than leaves produced in summer. Alternatively they were responding to shorter daylengths. Shoots had similar green leaf numbers until they had about 8 green leaves because leaf senescence started after the appearance of about 6-8 leaves. Leaf senescence was similarly affected by season; it was slower as temperatures declined and daylengths shortened from summer through autumn and winter and faster through spring into summer when temperatures and daylengths increased (Appendix 6). Leaf senescence was slightly slower in N26 than in NCo376 and N25. Leaf senescence was slowest in the April and May ratoon crops and the balance between leaf appearance and leaf senescence caused the number of green leaves to increase steadily until shoots had about 14 green leaves. Crops started in March, August, and December deviated from the trend set by the April and May ratoons by having fewer green leaves per shoot because they had higher rates of senescence and lower rates of leaf appearance (phyllochron 2 of August and December ratoon crops).

Cumulative thermal time during the first four months was a major factor driving leaf appearance rate (as evidenced by phyllochrons) and therefore in determining leaf area per shoot according to crop start date. Larger leaves appeared in the first four months of the December ratoon crop so that leaf area per shoot was higher than in all other start

dates. The temperatures between December and March were high and therefore cumulative thermal time was higher than any other start date. In the crops started in May the cumulative thermal time was lowest after four months because temperatures were lower from May to August. Differences in leaf area per shoot of young ratoon crops were linearly related to cumulative thermal time. As crops experienced wider temperature ranges with increasing age the differences in leaf area per shoot due to crop start date became less. When the crops had grown for 12 months leaf area per shoot tended to range between 0.2 m^2 and 0.3 m^2 (the highest were attained by May and December ratoon crops) in crops of all ratoons. N26 had the highest leaf area per shoot in each of the ratoon crops.

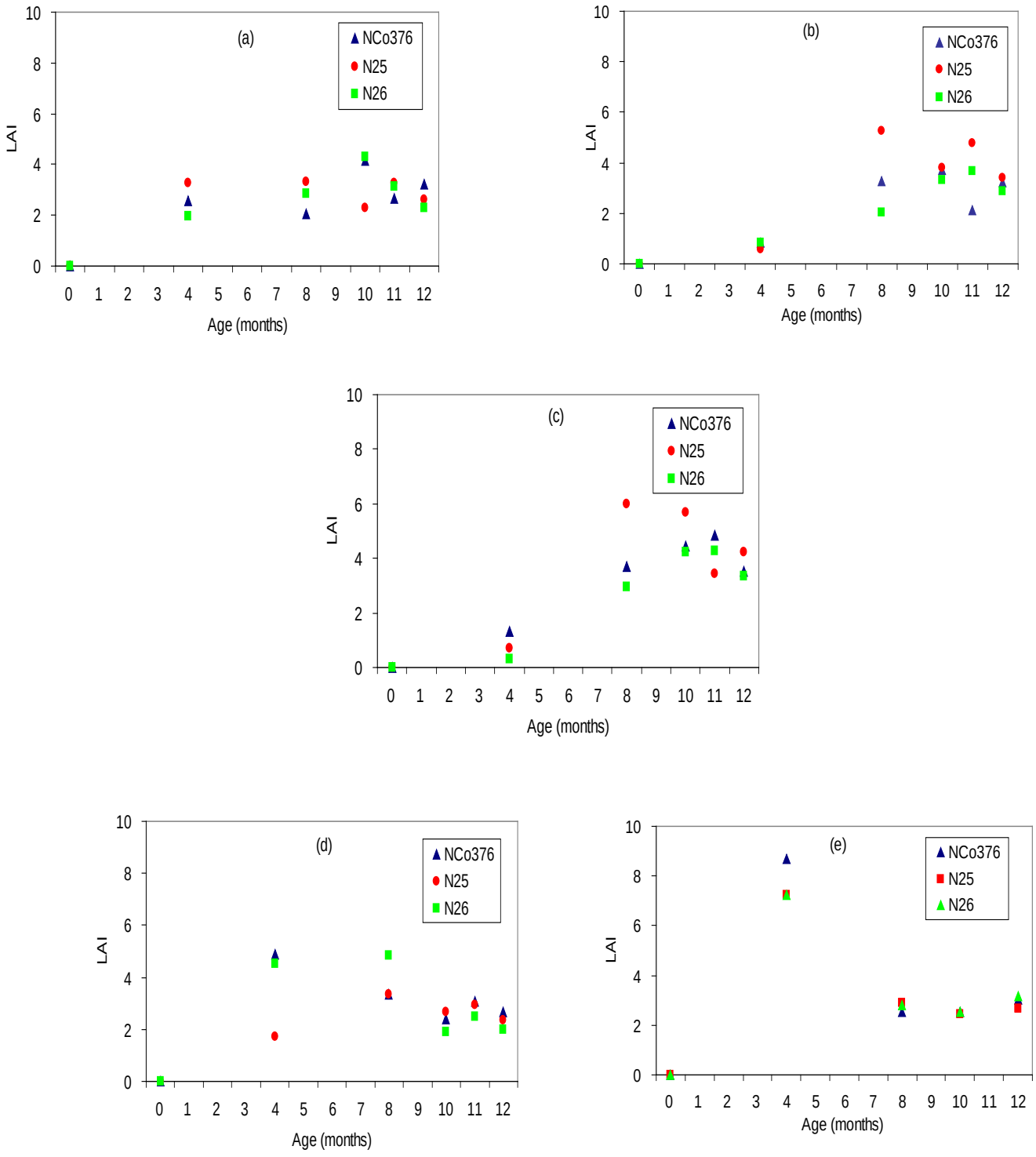


Figure 31 Development of green leaf area index (LAI) of the sugarcane cultivars NCo376, N25 and N26 over time in (a) March, (b) April, (c) May, (d) August and (e) December ratoons. No measurements were done at the age of 11 months in the December ratoon crops.

CHAPTER 5

GREEN LEAF AREA INDEX AND RADIATION INTERCEPTION

5.1 Introduction

In Chapter 3 it was shown that shoot emergence and the tillering processes are also mainly temperature driven and that it could take between 70 and 182 days for crops to reach SDmax, depending on the climatic factors operating during which the shoots emerged. In Chapter 4 it was shown that L ranged from <0.05 to 0.4 m^2 after four months of growth and that this variation was largely due to the influence of temperature on leaf development. The product of green leaf area per shoot L (m^2) and number of shoots in a defined area (m^2) per unit of land area is the green leaf area index (LAI) (dimensionless). Within a particular canopy structure LAI provides a crude indication of the crop's capacity of capturing radiation that drives photosynthesis. It does not consider the angle or orientation of leaves within the canopy. The rate at which canopies develop largely determines the fraction of total incident radiation that the crop is likely to intercept during a period of growth. When canopy development is fast the period when incident solar radiation is fully intercepted is longer than when canopy development is slow; crops with fast developing canopies will therefore be supplied with more energy than crops with slow developing canopies. If the production of crop biomass is linearly related to cumulative intercepted solar radiation (Muchow *et al*., 1994; Sinclair & Muchow, 1999) it then stands to reason that crops that intercept the highest fraction of incident solar radiation are likely to produce the highest biomass yields. The objectives of this chapter were to establish (1) how radiation is intercepted by crops that start growing in March, April, May, August and December and (2) whether radiation is intercepted differently by different cultivars (NCo376, N25 and N26). This information, together with biomass yields discussed in Chapter 9, is necessary to determine radiation use efficiency (RUE) and how it may be influenced by crop start date.

5.2 Results and Discussion

5.2.1 Green leaf area index

Cultivar trends in LAI over time were generally similar, with the obvious exception of higher values attained by N25 during the April and May crops (Figure 31). The LAI is a function of leaf appearance and senescence rates, leaf size and shoot density. The cultivars NCo376 and N26 attained peak LAI at an older age in May ratoon crops. LAIs

of NCo376 and were smaller in May ratoons, than in N25 (Table 8). LAI of N25 peaked by 4 months of age in the December ratoons and by 8 months of age in the ratoons. In August ratoons of N26 and NCo376 LAI peaked at the age of 4 months when they attained values between 4.5 and 4.9. In comparison, the August ratoon of N25 LAI peaked later (at the age of 8 months) and attained a lower value of 3.4. LAI values >7 were attained in December ratoons at the age of 4 months. This was due to high L and high shoot densities having developed early in the December ratoon crops. After attaining a LAI greater than 7 at the age of 4 months, the December ratoons exhibited a loss in LAI and values were between 2 and 3 when the crops were 8 months old. The LAI was then maintained at low values as the crops aged. This was similar in the cultivar N14 which developed a LAI of >7 between the ages of 6 and 8 months in crops started in April, August and October (Thompson, 1991). In the Thompson (1991) study, LAI declined to about 3 after the age of 10 months in all three ratoon crops. LAI remained >3 in April and May ratoons until the age of 12 months and approached 2 in March, August and December ratoons.

Table 8 Maximum leaf area index (LAI) values and in parenthesis, age (months) at which peaks were attained in NCo376, N25 and N26 in March, April, May, August and December ratoons.

Crop start month	NCo376	N25	N26
March	4.2(10)	3.3 (8)	4.2 (10)
April	3.8 (10)	5.3 (8)	3.7 (11)
May	4.9 (11)	6.0 (8)	4.2 (10)
August	4.9 (4)	3.4 (8)	4.5 (4)
December	8.7 (4)	7.2 (4)	7.3 (4)

5.2.2 Incident solar radiation

The age for the sampling when crops were 12 months old varied from 357 days in the December crop to 365 days in the April crop (Table 9). The total incident solar radiation, varied little between the five ratoon start dates (Figure 32) and was lowest at 6 544 MJ m^{-2} for the March ratoon and highest at 6 695 MJ m^{-2} for the April ratoon; the difference between these two crops being 151 or 2.3%, which is of little significance as all the crops grew through all the months of the year.

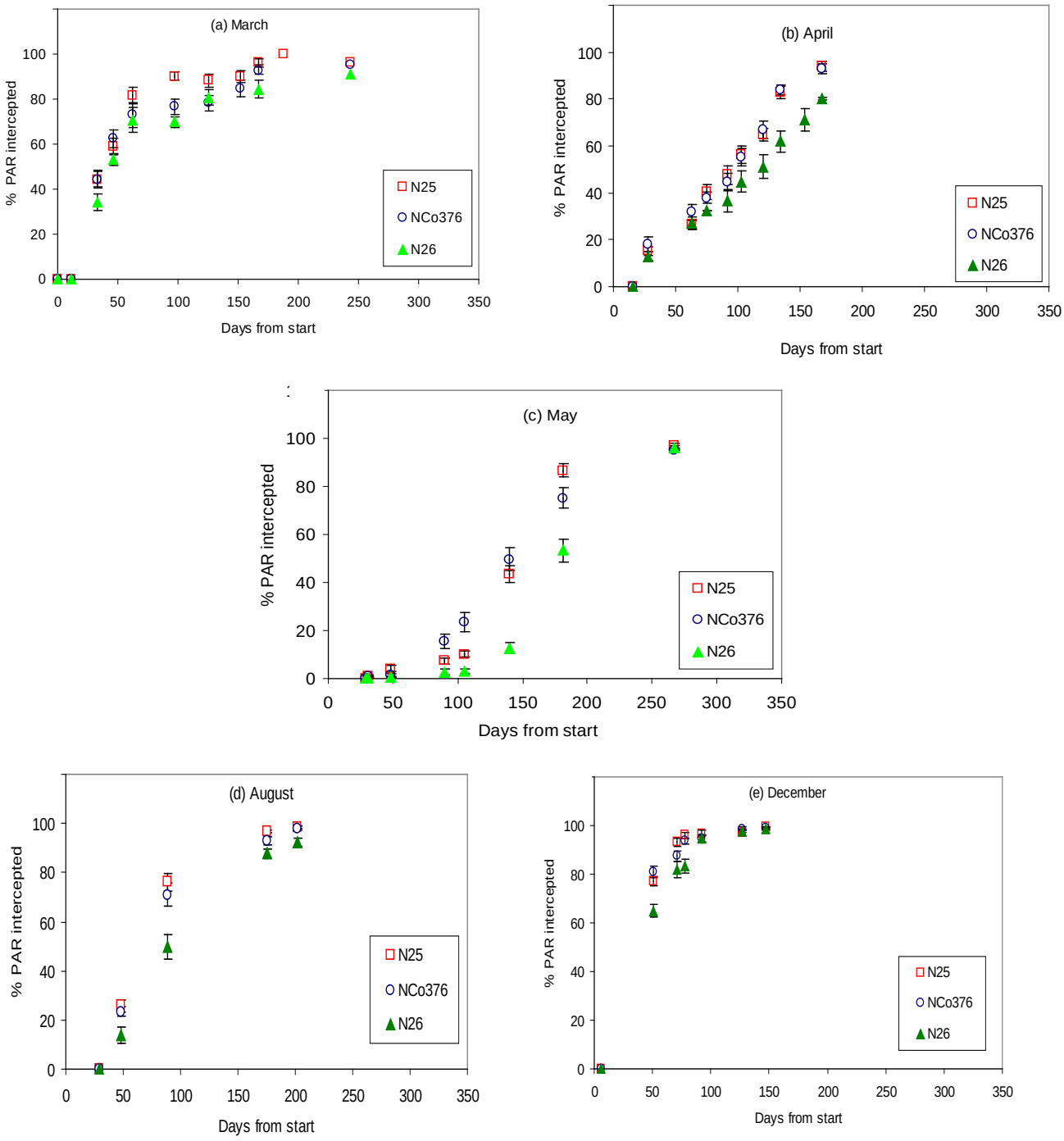


Figure 33 Data points of fractional intercepted PAR in developing canopies of NCo376, N25 and N26 crops of (a) March, (b) April, (c) May, (c) August and (e) December ratoons. Bars denote standard errors (P=0.05).

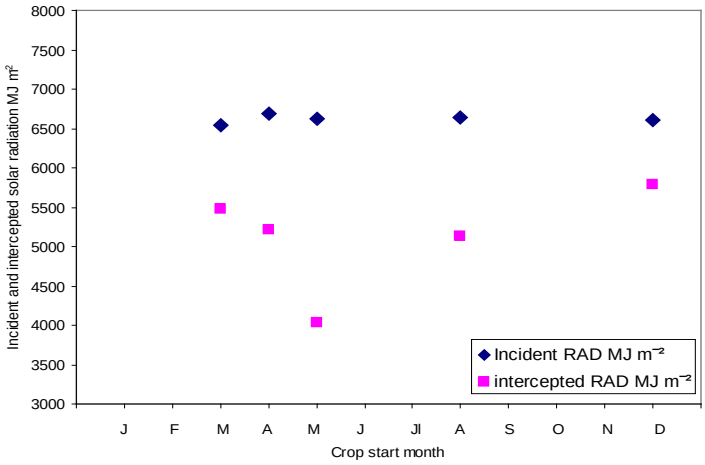


Figure 32 Variation in total incident and mean annual intercepted solar radiation (RAD, MJ m^{-2}) of mean values for the sugarcane cultivars NCo376, N25 and N26 ratoons started in March, April, May, August and December.

5.2.3 Effects of crop ratoon date on radiation interception

Daily intercepted solar radiation was estimated from polynomials fitted to measure PAR (Figure 33 and 2.4.5). The fraction of intercepted seasonal solar radiation varied greatly from 0.63 (average of NCo376, N25 and N26) in the May ratoon crop to 0.88 in the December ratoon crop. The results are similar to an earlier study at La Mercy (29° 34´N, 30° 8´E, 72 m altitude), in which June ratoon crops intercepted 0.61 of annual PAR (photosynthetically active radiation) compared to 0.82 by February ratoon crops - the effect of crop start date on the efficiency of radiation interception was highly significant (Inman-Bamber,1994b). It should be noted that the crops of the La Mercy study were not irrigated which is partly the reason for the low interception. In the present study the calculated mean cumulative intercepted solar radiation in the May ratoon was only 4 035 MJ m^{-2} compared to the 5 794 MJ m^{-2} in the December ratoon, i.e. the May ratoon intercepted 30% less radiation than the December ratoon. This is directly attributed to the slow development of the canopy in the May ratoon which was subjected to low temperatures (<15°C for 22 weeks) during shoot emergence and canopy development. The variation in the fraction of radiation intercepted can be attributed to the various factors that influence canopy development. These are the number and rate of shoot development together with number, rate and size of leaf development that govern the development of leaf areas and consequently LAI. Angles of leaves affect the way radiation is intercepted as described by the extinction coefficients (*k*). The May ratoon,

having started growing during a period of low temperatures (<12°C for 7 weeks) took on average 195 days before intercepting 75% of incident solar radiation (Table 9). In contrast, the canopy development of the December ratoon was much more rapid and reached the same stage of radiation interception after 53 days. Thus, the canopy of the May ratoon took 142 days (or 181°C d, base 16°C) longer than the December ratoon to reach a point of intercepting 75% of incident solar radiation. The trends in the season effects on radiation interception (Figure 34) are very similar to those recorded by Inman-Bamber (1994b).

Table 9 Cumulative intercepted solar radiation (iRAD) and fraction of incident solar radiation intercepted at different ages (days) and number of days taken for canopies to intercept 75% of incident solar radiation in NCo376, N25 and N26 crops started in five different months.

Crop - age (days)	Mar 362	Apr 365	May 362	Aug 362	Dec 357
iRAD (MJm^{-2})					
NCo376	5 443	5 296	4 436	5 175	5 849
N25	5 685	5 302	4 441	5 409	5 870
N26	5 283	5 025	3 228	4 786	5 662
Mean	5 464	5 208	4 035	5 123	5 794
± SD	191.8	158.2	698.9	314.7	144.5
Fraction iRad					
NCo376	0.83	0.79	0.67	0.78	0.88
N25	0.87	0.79	0.67	0.82	0.89
N26	0.81	0.75	0.56	0.72	0.86
Mean	0.84	0.78	0.63	0.77	0.88
± SD	0.031	0.023	0.064	0.050	0.015
Days to 75% iRad					
NCo376	76	132	183	101	48
N25	65	131	177	91	48
N26	91	160	224	134	63
Mean	77	141	195	109	53
± SD	13.1	16.5	25.6	27.6	8.7

5.2.4 Cultivars and radiation interception

The cultivar N26 lagged behind NCo376 and N25 in the cumulative intercepted radiation in all crops (Figure 33). The differences between N25 and N26 in the cumulative annually intercepted radiation were most evident in the May and August ratoon crops. In these crops N26 intercepted 11 and 10% less radiation than N25 (Figure 34). Interception of radiation by N25 was only slightly higher (<5%) higher than that of NCo376 in March and August ratoons. The cumulative annual amounts radiations

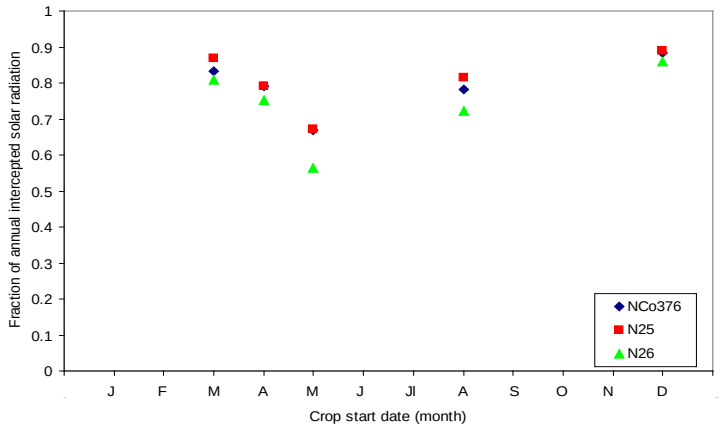


Figure 34 Fractions of annual solar radiation intercepted by NCo376, N25 and N26 of March, April, May, August and December ratoons.

intercepted by NCo376 were very similar to those intercepted by N25. The fractions of annually intercepted radiation indicated that the crops that reached full canopy in relatively few days (March and December) and rapidly displayed a LAI > 3.5, intercepted the highest fraction of incident solar radiation (Figure 31). Substantially lower fraction (0.56) was intercepted by N26 in the May ratoon compared with N25 and NCo376 (0.67) (Figure 34). This was due to the relatively slower foliar development of N26 at low temperatures (>12°C) (Figure 31) (Singles *et al*., 2005a). In the August ratoon crop N25 intercepted the highest fraction of radiation when the crop was about 150 days old. The LAI developed at 4 months of age ranged between 0.31 (N26 May ratoon) and 8.7 (NCo376 December ratoon) and the instantaneous percentage of radiation intercepted ranged between 15.7 and 98.5% (Figure 35). This relationship suggests that when

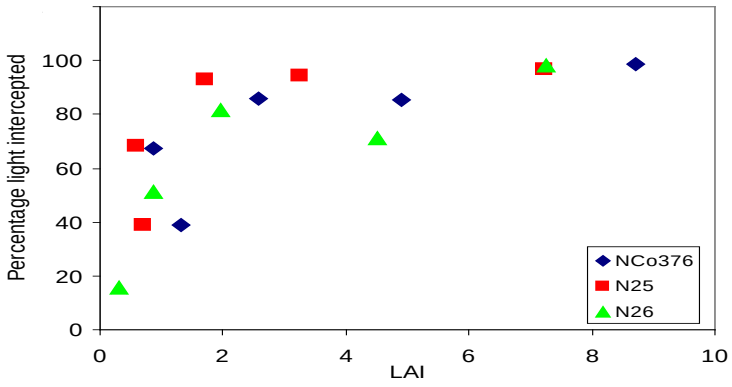


Figure 35 LAI of N25, N26 and NCo376 at the age of 4 months and estimated percentage of solar radiation intercepted by March, April, May, August and December ratoons.

LAI=2 the N25 crop was capable of intercepting > 90% incident radiation. LAI and its associated intercepted PAR was selected from each of the five ratoon crops to create a range of LAIs ranging from <1 to >7 for each of the three cultivars to calculate *k*.

5.2.5 Extinction coefficients *(k)*

The calculated extinction coefficients (*k*) ranged between 0.37 (N25) and 0.46 (N26) with an intermediate value of 0.41 for NCo376 (Figure 36). When all data from the three cultivars were combined then *k* was 0.40 when interception was measured as PAR. Previously *k* values, calculated from intercepted solar radiation, of 0.38 (Muchow *et al.*, 1994) and 0.40 (Muchow, Evensen, Osgood & Robertson, 1997) have been calculated in studies done in which Australia and Hawaii, respectively. The *k* value of 0.4 is at the bottom of the range (0.4 - 0.7) indicated for Perennial ryegrass, rice and maize by Hay & Walker (1989).

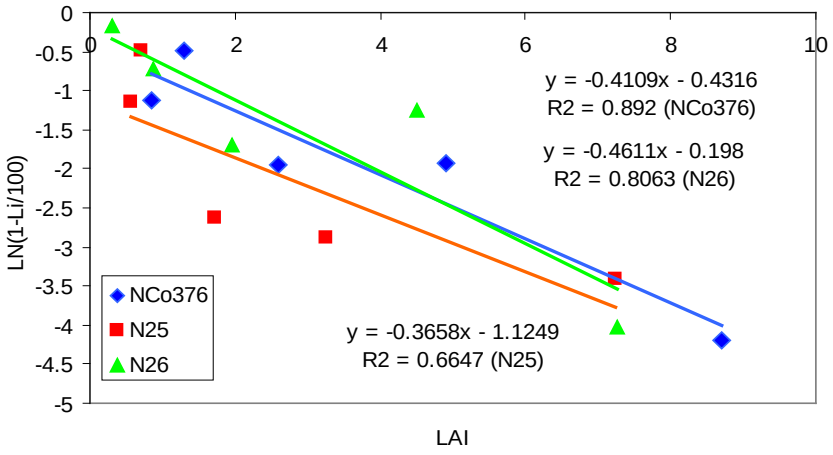


Figure 36 Relationships between fractions of PAR intercepted and green leaf area index (LAI) of the sugarcane cultivars NCo376, N25 and N26. The linear equation for the combined radiation interception of all three cultivars is y = -0.403x - 0.6161, R^2=0.7444.

There were insufficient data to show seasonal effects on *k,* however, it was interesting that the May ratoon crops of NCo376 and N25 intercepted a lower fraction of radiation (38.8%) at a higher LAI (0.7 to1.3) than the April ratoons (68% at 0.57 to 0.87). During the early growth of the May ratoon (in the present study) leaves were smaller (Figure 23) and O'Leary & Donaldson (2000) found that mean leaf angle (from the horizontal) of the cultivars NCo376 and N26 changed from 35°- 50° (erect), when LAI was very low (<1.0), to 20°-30° (less erect) when LAI was 1 to 2. By interpolation it is possible that a more erect leaf orientation in the May ratoon crop was the reason for intercepting less

radiation, than if leaves were more prostrate, even when LAI was higher. Inman-Bamber (1991b) found that for NCo376 grown at 1.2 m row spacing *k* was 0.56 when there were less than 15 leaves per shoot (LAI <2) and changed to 0.86 when LAI was between 2 and 4.5. In a study in Zimbabwe Zhou *et al*., (2003) showed that *k* increased steadily from 0.48 after 87 days of growth to 0.61 after 131 days in a plant crop of NCo376 grown at 1.5 m row spacing. Collectively the above data show that *k* values in sugarcane increased when a larger portion of planophile and fewer erectophile leaves were at the top of shoots and LAI was increasing. There was no evidence of accelerated leaf senescence when LAI exceeded 2 and the fraction of PAR intercepted was nearly 100% in N25. Predictions that leaf angle would have little effect on rates of canopy photosynthesis when LAI was less than 3 were made from simulations of maize (*Zea maize* L) (Duncan, 1971). Subsequent to this analysis (Duncan, 1971), yield advantages in maize genotypes with upright leaves were observed in experiments only when LAI was high (Pepper, Pearce & Mock, 1977). Sugarcane leaves are not known to track solar radiation (heliotropism), however, the author often found leaf sheaths that were slightly twisted around the stalk. This may have been evidence of diaheliotropism (shade avoidance) in sugarcane which allowed the leaves in the lower strata of the canopy to orientate them so as to avoid total shade. A change in radiation quality (lower R:FR ratio) together with quantity of radiation was the trigger of leaf senescence in sunflower (Rousseaux, Hall & Sánchez, 1996). The ability of sugarcane leaves to orientate themselves to avoid total shade could the reason that they survived in lower strata of the canopy where illumination was very low and when LAI was high.

5.3 Concluding Discussion

The canopy architecture in the ratoon crops changed with age. During very early canopy development O'Leary & Donaldson (2000) found that leaves were more erect. Erect leaves are strongly illuminated. As canopy development advanced shoot production continued by tillering and larger leaves were added to the LAI. In more advanced stages of canopy development larger leaves, which assumed a more planophile orientation as they aged were added to the canopy. The canopy was then comprised of relatively erect newly formed leaves at the top of the canopy and more horizontally arranged leaves in lower strata of the canopy. This arrangement of leaves allowed for maximum interception of solar radiation (giving high *k* values) as the sun angle changed throughout the day (Irvine, 1972). LAI increased during a period when larger leaves were

being added to the canopy, tillering rate was high and senescence affected only the smaller first leaves at the base of the shoot. At more advanced stages of development, senescence affected larger leaves and shoots were dying rapidly and this was the most likely cause of LAI being reduced, particularly in the December ratoon crops.

It was estimated that an LAI of 2 in some sugarcane cultivars is sufficient to intercept incident solar radiation fully. It has previously been observed that incident solar radiation is fully intercepted (Li = 1) when LAI in sugarcane exceeds approximately 2.0 (Inman-Bamber, 1990 cited in Thompson, 1991). Once canopy closure was reached in the present study, LAI >2 was maintained at all times and losses in productivity could then not be ascribed to poor radiation interception. The very low *k* values measured in this study may be have been due to the method of selecting LAI and their associated Li (PAR) from several young ratoons compared to other studies (Inman-Bamber, 1991b; Zhou *et al*. 2003). In the studies by Inman-Bamber (1991b) and by Zhou *et al*. (2003) several successive measurements of LAI and Li were made on a developing canopy of a single crop. The cultivars N25, NCo376 and N26 intercepted similar fractions of incident radiation. The exception was the low fraction of interception by the N26 May ratoon crop. The low fraction of intercepted seasonal radiation of N26 in the May ratoon was due slow canopy development. This is symptomatic of the cultivars slower production of new shoots (tillering), rather than reduced leaf area per shoot, during winter months when temperatures were lower.

Season had a marked effect on the efficiency of radiation interception. The time taken by canopies to reach full interception of incident solar radiation largely determined the fraction of annual incident radiation that was intercepted. The lowest mean fraction of annual interception was 0.63 for the May ratoons and this was due to slow canopy development. In the December ratoons canopy development was rapid due to larger leaves and rapid tillering, driven by higher temperatures and longer day lengths. The average fraction of intercepted annual solar radiation of the five ratoon dates for the three cultivars was highest in the December ratoons at 0.88. The cumulative annually intercepted radiation was lower in April than March and lower in May than April ratoons (Table 9). In August ratoons annual intercepted radiation was similar to than of the April crop. One could therefore expect biomass yields to follow the same trends as for intercepted solar radiation.

CHAPTER 6

FOLIAGE AND TRASH PRODUCTION

6.1 Introduction

Thick layers of trash may retard regeneration of sugarcane ratoon crops. Knowledge of seasonal production of trash may be used to predict situations in which ameliorants may be needed to accelerate its decomposition when quantities become excessive following high yielding crops. While trash is decomposing nutrients are released from it to the soil and this should be considered when determining the appropriate fertilizer programmed for maximizing sugarcane productivity when green cane harvesting is practiced. Advances in technology addressing ethanol production from lignocelluloses will also enhance the value of sugarcane trash. The objective of this part of the study was to quantify the trash and stalk components of above-ground biomass in relation to cultivar and crop start dates. The quantities of biomass and trash that were produced by NCo376, N25 and N26 in March, April, May, August and December ratoons were quantified and these could serve as a record of potential annual biomass and trash yields of commercially grown cultivars in South Africa under conditions free of diseases and water stress. It should be noted that potential trash refers to the sum of dead trash and green foliage. Where the term trash is used it is the same as potential trash which is comprised of dead foliage and dead shoots (tillers) and green leaves. Trash that contained small amounts of stalk material probably resulted in an over estimation of dry matter content and this may have contributed to some of the variation in the estimation of trash production in this study. Some trash was consumed by arthropods but the amounts were small and were of little significance to calculations of biomass yields.

6.2 Results and Discussion

6.2.1 Partitioning of biomass to trash

During early stages of sugarcane growth the above-ground biomass is composed entirely of green foliage because stalk tissue only appears above-ground after about eight leaves have emerged (Robertson *et al*., 1998). Thereafter the fraction of foliage in above-ground biomass decreases as the stalk mass increases (Thompson, Figure 2, 1978). When the radiation environment within the cane canopy triggers shoot senescence, dead and dying shoots add to the trash component.

In the present study, the rate of shoot senescence was more rapid in the August and December ratoons than in the March, April and May ratoons (Figures 13, 14 and 41). May and August ratoons produced significantly (P=0.05) lower fractions, and December crops higher fractions, of trash (Table 10). There were also significant cultivar x starting

Table 10 Yields of green trash, dead trash, total trash and fractions of total trash in biomass of the sugarcane cultivars NCo376, N25 and N26 in March, April, May, August and December ratoons at the age of 12 months (Statistical analysis is in Appendix 1(e))**.**

Cultivar and ratoon month	Green trash (g m^{-2})	Dead trash (g m^{-2})	Total trash (g m^{-2})	Total trash as a fraction of biomass
NCo376				
Mar	1 277	975	2 252	0.349
Apr	1 176	1 214	2 390	0.317
May	672	952	1 624	0.253
Aug	508	1 019	1 527	0.245
Dec	832	882	1 714	0.350
N25				
Mar	1 012	765	1 777	0.311
Apr	842	988	1 830	0.299
May	953	790	1 743	0.276
Aug	529	903	1 432	0.246
Dec	675	899	1 574	0.343
N26				
Mar	778	550	1 328	0.266
Apr	848	1 047	1 895	0.289
May	976	669	1 645	0.276
Aug	483	904	1 387	0.266
Dec	958	926	1 884	0.363
Means				
Ratoon month				
Mar	1 022a	763a	1 786a	0.309a
Apr	955a	1 083b	2 038ab	0.302b
May	867a	804a	1 671a	0.268c
Aug	507b	942b	1 449ac	0.252c
Dec	822b	902a	1 724a	0.353d
Cultivar				
NCo376	893a	1 008a	1 901a	0.303a
N26	802a	869b	1 671b	0.292a
N25	809a	819b	1 628b	0.295a
Cultivars SED	53	35	67	0.01
LSD(0.05)	104	69	131	0.02
Cultivar X month SED	118	78	149	0.017

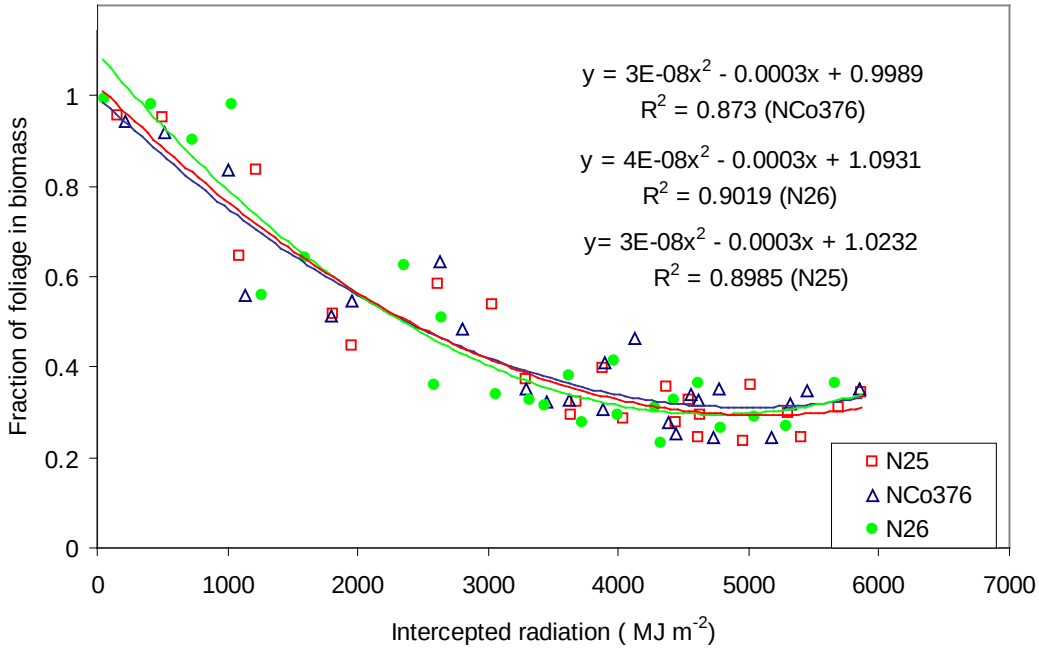


Figure 37 Changes in fractions of foliage in biomass of N25, NCo376 and N26 in relation to intercepted radiation of March, April, May, August and December ratoons.

month interactions such that fractions of trash at 12 months of age were significantly (P=0.05) higher in NCo376 than in N25 and N26 in the March and April ratoons. The reverse was true in the May ratoon so that trash fractions of NCo376 < N25 and N26 (P=0.05). In the August ratoon the trash fraction was significantly higher (P=0.05) in N26 than N25 and NCo376; the trash fraction in the December ratoon was significantly higher in N26 than in N25 (Table 10). The relationships between the fractions of foliage (destined to become trash) in above-ground biomass (Figure 37) show that there was greater variation of foliage fractions (total trash) in above-ground biomass at about 1000 MJ m⁻² intercepted radiation than when intercepted radiation exceeded 3000 MJ m⁻² . The average fraction of foliage in above-ground biomass was similar for NCo376, N25 and N26 when the crops were 12 months old (Table 10).

6.2.2 Trash yields of 12-month old crops

Trash yields were generally highest in March and April ratoon crops, and were lower through winter (May ratoons) into spring (August ratoons) and ranged from 1 328 to 2 390 g m⁻² (Table 10). The trash fractions in biomass suggest that trash production was

lower (due to lower leaf senescence) through the winter months and was higher in the summer months. Trash yields were higher in December ratoons despite their lower biomass yields and this was due to higher rates of shoot senescence so that partitioning fractions to trash were higher. These trends were similar in data represented by a wider range of cultivars presented by Donaldson *et al.* (2008b).

6.2.3 Dead and green components of trash

There are essentially two layers to a trash mulch blanket. The lower layer consists of decomposing dead shoots that are shaded out during crop development, together with dead leaves that are sloughed from older stalks. This is overlaid by a second layer composed of dead leaves and green plant material which are parted from the stalks when the crop is harvested. The green trash is composed of green leaves and short immature stalk tops. Plant nutrients are continuously translocated from dying tissue into vigorously growing parts of the sugarcane plant, and therefore the top layer of green trash will contain most of the nutrients that can be recycled into the soil when the trash decomposes (van den Berg, Jones & Van Antwerpen, 2006). The amounts of dead trash and green trash and their rates of decomposition determine how nutrients and organic matter are recycled to the soil. Foliage, as a fraction of above-ground biomass, was

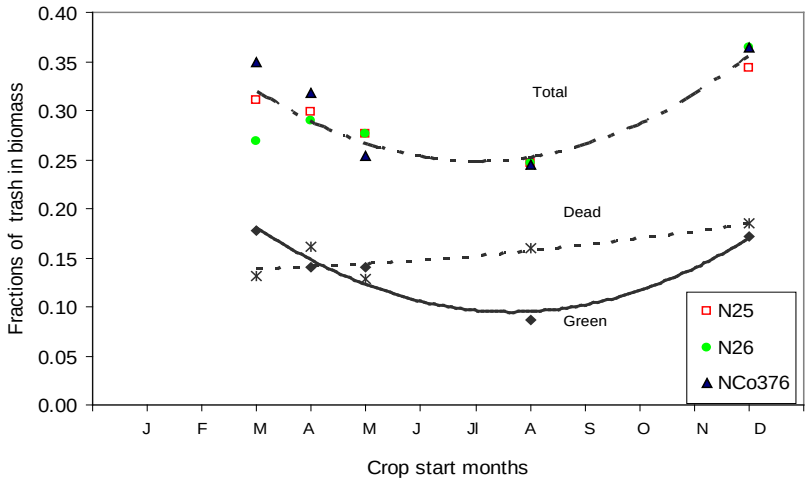


Figure 38 Fractions of total foliage of the sugarcane cultivars N25, N26 and NCo376 and mean dead trash and green trash fractions in above-ground biomass of March, April, May, August and December ratoons.

lower in March, April and May and was higher in August and December (Figure 38). The green trash fraction followed a seasonal trend in similar fashion to the total foliage. The

mean fraction of dead trash fraction ranged from 0.13 in March and April to 0.18 in December and appeared to have followed a linear trend from March to December. The components of the trash mulch blanket (i.e. green and dead components) therefore changed during the season and this may affect the rate at which, and the amounts of nutrients that are returned to the soil (van den Berg *et al*., 2006) from annual ratoons harvested at different times of the season.

6.2.4 Predicting trash yields from cane yields

Cane yields (stalk fresh mass) are sometimes used to predict the amount of trash that may be expected from an existing crop (Thompson, 1966). Because the water content in sugarcane stalks is not easily predicted, only biomass (dry mass) is used in many studies. Thus, the relationship between trash dry mass and cane fresh mass may not be reliable because of the variable water content in sugarcane stalks. The relationship may nevertheless be used to develop 'rules of thumb' that can be useful for predicting amounts of trash quickly. The relationships between trash and cane yields were curvilinear for NCo376, N25 and N26 (Figure 39). Thompson (1966) estimated the

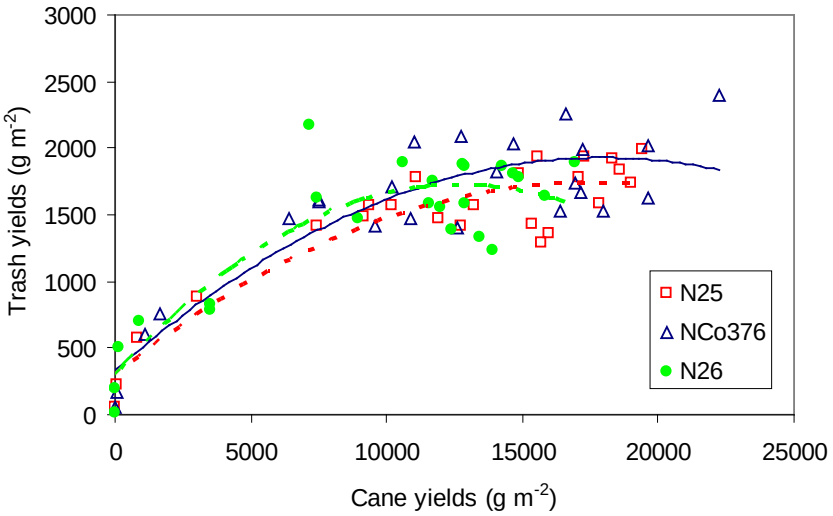


Figure 39 The relationships between sugarcane stalk yields and total foliage (= trash) yields for the cultivars NCo376, N25 and N26 of March, April, May, August and December ratoons.

cane:trash ratio of annually harvested NCo376 grown under dryland conditions at 1.37 m row spacing to be 6:1. However, it was pointed out that row spacing, cultivar, age and cultural practices all affect this ratio (Thompson, 1966). Thompson (1966) gave no

indication of the effect of season on trash yields. The cane:trash ratios in the present study were calculated for N25, NCo376 and N26 (Table 11). The mean ratio across the three cultivars and crop start dates was 9.2:1. When N14 was added to the data a mean cane:trash ratio was 9.3:1 (Donaldson *et al*., 2008b). The linear model for N14: y = 0.0596x + 7.3605 (where x is fresh cane yield (t ha^{-1}), y is trash dry mass yield t ha^{-1}; predicts that a crop of N14 with a cane yield of 7 000 g m^{-2} will produce 1 150 g m^{-2} of total trash. The ratios determined in this study are higher than the 6:1 reported by Thompson (1966) for NCo376 grown under dryland conditions (except for the December ratoon). This could be expected because the crops in this study were well irrigated and grown at wider row spacing than in the Thompson (1966) study. Stalk tops were also included in the trash component of the NCo376 Thompson study (1966) but were not included in the ratios presented here (Table 11). The mean cane:trash ratio of the December ratoon crops was much lower than crops ratooned in other months, and this is associated with the low biomass yields reported in Chapter 9 and as published (Donaldson, Redshaw, Rhodes & Van Antwerpen, 2008a).

Table 11 Ratios of cane: trash yields of N25, N26 and No376 at the age of 12 months of March, April, May, August and December ratoons.

Cultivar	Mar	Apr	May	Aug	Dec	Overall means $\pm$ SD
N25	9.6	10.2	10.9	10.7	6.5	9.6 $\pm$ 4.40
NCo376	7.4	9.3	12.1	10.7	5.9	9.1 $\pm$ 2.49
N26	10.9	8.9	9.6	8.9	5.6	8.8 $\pm$ 1.96
Means	9.3	9.5	10.9	10.1	6.0	8.5
$\pm$SD	5.24	0.67	1.25	1.04	0.46	2.95

6.2.5 Stalk tops in crop residue

At the time of harvesting, the crop residue left in the field as trash is composed of

(i) dry material from dead and dying shoots (tillers) and senesced leaves,

(ii) green leaves on the stalk and

(iii) the top section of stalks that is cut off because it is enclosed in the green leaf sheaths and contains little or no recoverable sucrose.

Thus far, potential trash has been presented as the combined mass from (i) and (ii). Lengths of tops left as residue after harvesting vary greatly within a crop and between months of harvest. The dry mass per 10 mm length of the top 200 mm of the stalk,

Table 12 Dry mass (g 10 mm^{-1}) in the top 200 mm of stalks in annual sugarcane crops of NCo376, N25 and N26 started in March, April, May, August and December.

Ratoon month	Mar	Apr	May	Aug	Dec
NCo376	0.49	0.57	0.75	0.46	1.10
N25	0.68	0.48	0.77	1.22	1.46
N26	0.80	0.80	0.88	1.62	1.44

excluding the very soft apex of the stalk clearly varied across crop ratoons and differed between cultivars (Table 12). From these data the mass of tops of varying lengths can be estimated. For example, the dry mass of tops left as residue in the field from topping at a height of 150 mm below the stalk apex, was estimated to be 11.25, 11.55 and 13.20 g top^{-1} for NCo376, N25 and N26, respectively, in annual crops harvested in May. Using shoot densities of 18.45, 13.31 and 14.08 stalks m^{-2} this would amount to dry mass of 208, 154 and 186 g m^{-2} for the cultivars NCo376, N25 and N26, respectively.

6.2.6 Nutrient content in crop residue

The nutrients N, P and K percentages in trash, green foliage and whole stalks of annually harvested ratoon crops of N14 crops ratooned in April, August and October at Pongola were measured by Thompson (1991) (Table 13). The amounts of each nutrient in each of the trash components were also calculated (Table 14), assuming that the

Table 13 Nitrogen, phosphorus and potassium content (% dry matter) in components of the sugarcane cultivar N14 ratoon crops started in April, August and October according to Thompson (1991).

Crop ratoon month	Crop component	Yield of component (g m^{-2})	N (% dm)	P (% dm)	K (% dm)
April	Whole stalk	3 987	0.32	0.05	0.93
August	Whole stalk	5 505	0.25	0.03	0.83
October	Whole stalk	4 800	0.23	0.04	1.03
April	Dead trash	1 050	0.34	0.03	0.41
August	Dead trash	1 260	0.30	0.02	0.32
October	Dead trash	840	0.31	0.03	0.26
April	Green foliage	1 200	0.87	0.09	1.89
August	Green foliage	820	0.76	0.09	1.68
October	Green foliage	740	0.69	0.08	1.68

Table 14 Amounts of nitrogen, phosphorus and potassium (g m^{-2}) in components of annual crops of sugarcane cultivar N14 calculated from Thompson (1991).

Crop ratoon month	Crop component	N (g m^{-2})	P (g m^{-2})	K (g m^{-2})
April	Tops*	0.64	0.10	18.6
August		0.50	0.60	16.6
October		0.46	0.80	20.6
April	Dead trash	3.60	0.31	4.3
August		3.80	0.25	4.0
October		2.80	0.27	2.3
April	Green trash	10.4	1.08	22.6
August		6.2	0.73	13.7
October		5.1	0.59	12.4
April	Total above-ground	26.7	3.38	64.0
August	biomass	23.7	2.64	63.4
October	(including stalks)	18.9	2.78	64.2

*assuming tops have a mass of 200 g dry mass m^{-2}.

nutrients are distributed evenly along the length of stalks and that topping produces stalk residue of 200 g m^{-2} dry mass. From these calculations it is clear that substantial amounts of nutrients can be recycled in trash matter. In the Thompson (1991) experiment, up to 14.6 g N m^{-2} (146 kg N ha^{-1}), 1.5 g P m^{-2} (15 kg P ha^{-1}) and 28.7 K g m^{-2} (287 kg K ha^{-1}) could have been returned to the soil via the various trash components of N14 (Table 14), most of which were located in the green trash component. In contrast, Ramakrishnarao & Ramalingaswamy (1982) recorded that during burning of trash; most N was lost, as was up to 75% of P, Ca, Mg, K, Na and Zn, as well as other nutrients. It is tempting, then, to assume that fertiliser amounts can be reduced for cane crops following green cane harvesting. However, Ng Kee Kwong, Deville, Cavalot & Reviere (1987) showed that crop uptake of N from a trash blanket was negligible and that the N was largely immobilised in the soil organic matter. Other researchers (Thorburn, Probert, Lisson, Wood & Keating, 1999; Robertson & Thorburn, 2000, 2007a) have also encountered immobilisation of N during trash decomposition, due to high C:N ratios. This means that most of the N recycled in trash does not immediately become available to the following cane crop; Robertson & Thorburn (2007b) estimated the rate of N release from trash during first 12 months to be slow (1-5 kg N ha^{-1} $month^{-1}$), so that it would be of little immediate significance for plant growth. A period of adjustment to the trashed system is required before soil organic carbon and total nitrogen pools come into equilibrium; prior to this, fertiliser reductions should be made with caution. The period after which equilibrium is reached varies according to environmental conditions, and has been reported to range from between 5-10 years in South Africa (van Antwerpen, Thorburn, Horan, Meyer & Bezuidenhout, 2002) to between 20-30 years in Australia (Robertson &

Thorburn, 2007a). To maximise cane production benefits from trashing, Thorburn, Van Antwerpen, Meyer & Bezuidenhout, (2002) recommended initially applying up to an additional 60 kg N ha^{-1} under trashed conditions, to feed a bigger crop, but cautioned that economic and environmental soundness of this practice needed to be investigated.

6.2.7 Other aspects related to trash blankets

Trashing is a controversial issue in South Africa's sugar industry due to the obvious advantages and disadvantages inherent in the practice. The biggest impacts that a trash blanket have on the production of sugarcane are the suppression of water lost by evaporation (90 mm $annum^{-1}$; Thompson, 1966) from the soil surface and the reduced amounts of herbicides required to control weeds (Murombo, Takavarasha & Wiseman, 1997). Other advantages include the continuous protection of the soil surface against crusting (caused by impact energy of water droplets) on susceptible soils (SASRI Soil Identification and Management Working Group, 1999) and therefore improved water infiltration rates, reduced run-off and erosion, improved organic matter content and thus soil health (Van Antwerpen & Meyer, 1998). The minimum amount of trash required to realise these advantages is in the order of 10 tons trash ha^{-1} (1 000 g m^{-2}), which equates to a cane yield of about 60 tons ha^{-1} (6 000 g m^{-2}). The total trash produced by NCo376, N25 and N26 in each of the March, April, May, August and December ratoons exceeded this minimum amount of trash. Below this amount the advantages of a full trash blanket diminish, as is evident in the difference between spreading only the cane tops after burning at harvest, and retaining the trash following green cane harvesting. However, trash blankets can have a negative impact on cane yield when used in situations such as: (i) where the soils are continually wet (valley bottom soils with a water table within 500 mm from the surface for a portion of the growing season); (ii) exceptionally wet seasons before the crop has reached full canopy stage (van Antwerpen *et al.,* 2006); and (iii) areas prone to frosting or where minimum temperatures in winter are less than 2ºC.

6.3 Conclusions

Trash yields, which are the sum of dead trash and green foliage, varied greatly due to cultivars and season effects on growth. Trash yields ranged from 1 328 $g^{-}m^{2}$ produced by N26 in the March ratoon to 2 390 g m^{-2} produced by NCo376 in the April ratoon. On average, NCo376 produced significantly more trash than N25 and N26. April ratoons produced significantly more trash than March, May, August and

December ratoons. August ratoons produced significantly less trash than March, April, May and December ratoons. Large amounts of trash, exceeding 2 000 g m^{-2} (20 t ha^{-1}), were only produced by NCo376 in ratoon crops started in March and April. The need for ameliorative action to mitigate negative effects of large amounts of trash therefore appears to be limited. A cane:trash yield ratio of 9:1 may be reasonably accurate for estimating trash yields of crops grown under irrigation in the northern regions of the South African sugar industry. Trash contains large amounts of nutrients (for example up to 14.6 g N m^{-2}, 1.5 g P m^{-2} and 28.7 K g m^{-2}) ; benefits from recycling nutrients through trash and improving soil health are, however, only likely to be realised over the long term. Monitoring the nutrient status in soil and leaf samples will be essential in determining how to adjust fertiliser programmes in the long term of crops grown with trash mulches.

CHAPTER 7

STALK DEVELOPMENT

7.1 Introduction

The sucrose that is accumulated in sugarcane stalks provides the energy required for germination and early growth of the shoots and roots. Sugarcane stalks are harvested and processed to recover the sucrose for the production of commercial sugar. The size and number of sugarcane stalks therefore have a major influence on the storage capacity and yield potential of a crop. The sugarcane stalk grows by addition of internodes at its apex, by elongation of newly formed internodes and by an increase in the girth of nodes and internodes (Sinclair *et al*., 2005). The volume of internodes increased up to a maximum at internode 15 regardless of cultivar and time of harvest in Florida, USA (Sinclair *et al*., 2005). After internode number 15 the volume of internodes decreased in a continuous manner (Sinclair *et al*., 2005). However, while the pattern of internode sizes was consistent among four cultivars the actual volumes of comparative internodes were different in August and January harvests. Volume differences between internodes up to number 25 from an August and January harvest were due to differences in diameter rather than internode length (Sinclair *et al*., 2005). Lingle (1999), working in New Orleans, USA showed that internode elongation was complete after about 380°C d (base temperature 18°C) and continued to accumulate dry mass for twice as long (800°C d). The accumulation of total sugars (brix) followed a logistic curve during the growth of internodes studied by Lingle (1999) and while the ratio of sucrose to total sugars initially decreased it later rose and was close to 1 at maturity. As the dry matter content increased the water content decreased from about 920 g kg^{-1} fresh weight to about 710 g kg^{-1} in a mature internode. In a range of South African cultivars studied by Inman-Bamber (1996) sucrose percentage rose rapidly in young internodes and then more gradually as the internodes aged. Sucrose levels reached levels of 55% dry mass in the base of the stalks during winter. The sucrose content further up the stalk was dependent on distance from the natural breaking point (a point below the stalk apex at which the stalk breaks when leaves are stripped of the top of the stalk) and the number of green leaves on the stalk. When compared with the standard South African industry cultivar, NCo376, the sucrose content in stalks of other commercially important cultivars in 1996 ranged from 2% less than that of NCo376 to 35% more than in NCo376. Higher stalk sucrose content was due either to increased dry matter content, higher sucrose content, or due to higher levels of both these components. Variations in sucrose content of the whole stalk arose from differences in the portion

of expanding internodes to fully expanded internodes and to a lesser extent on the influence of date of sampling (season) on sucrose levels (Inman-Bamber, 1996).

Ultimately the sucrose yield of a cultivar depends on the sucrose mass accumulated by individual stalks and the final number of stalks harvested. A cultivar that has many stalks that accumulate relatively low amounts of sucrose can yield as much sucrose per hectare as a cultivar that has fewer stalks that accumulate larger amounts of sucrose. Previous studies have indicated that the most important factors that influence sucrose accumulation in the sugarcane culm are season (time of year), age, as well as cultivar characteristics that are under genetic control. The aim of this chapter is to elaborate on the influence that each of these factors has on the accumulation of sucrose by individual stalks of N25, N26 and NCo376.

7.2 Results and Discussion

7.2.1 Stalk emergence

Shoot development begins when subterranean buds germinate and shoot initials grow towards the soil surface. The aerial shoots were composed of bracts and leaves during this early phase of growth and no stalk material was present amongst the aerial shoot material. Inspection of shoots with different number of leaves revealed that stalk (culm) apices first started appearing in shoots cut at ground level when they had nine leaves (Appendix 4). This was in agreement with Robertson *et al.* (1998) who found that the first eight leaves are attached to subterranean nodes. The thermal times of the first phyllochron of each starting date for each cultivar (Table 5, Chapter 4) were multiplied by nine to estimate the thermal time required by stalks to grow to the soil surface and to start emerging within the leaf sheaths above the soil surface (Table 15). The average thermal times required were very similar for the autumn and winter started crops, shorter for August ratoons and longer for December ratoons. On average stalks were calculated to have emerged after 64, 94, 104, 71 and 64 days, which were equivalent to 851, 835, 817, 724 and 986°C d (base temperature 10°C) for March, April, May, August and December ratoons, respectively. The lower thermal times of March ratoons through to August and then the higher thermal times of the December ratoons suggest that daylength and other endogenous factors may have influenced stalk emergence. Low soil moisture was ruled out as a factor affecting germination because all previous crops had only been subjected to very short drying off periods before harvesting.

Table 15 Calculated thermal time (°C d , base 10) for stalk (culm) emergence in the sugarcane cultivars N25, N26, NCo376 of March, April, May, August and December ratoons.

Start month	March	April	May	August	December	Over all mean ± SD
Cultivar	°C d	°C d	°C d	°C d	°C d	°C d
NCo376	874	918	874	770	1022	891.6 ± 90.9
N25	797	804	677	715	968	792.2 ± 112.1
N26	882	782	900	687	968	843.8 ± 110.6
Mean	851.0	834.7	817.0	724.0	986.0	842.5 ± 105.8
± SD	46.9	73.0	121.9	42.2	31.2	

7.2.2 Stalk heights

Stalks continued to elongate throughout the sampling period in the March ratoon crop (Figure 40). However, there were indications that maximum heights were attained before the final sampling in the April N25 and NCo376 crops. Maximum stalk height was reached earlier in the May, August and December ratoons. Stalk heights increased little after the age of 8 months in the August and December ratoons. All three cultivars attained heights exceeding 2.0 m in the December ratoons and close to 3.0 m in the August ratoons, at 12 months of age. Heights close to 3.0 m were also attained in the March, April and May ratoons after 13 months of growth. The N26

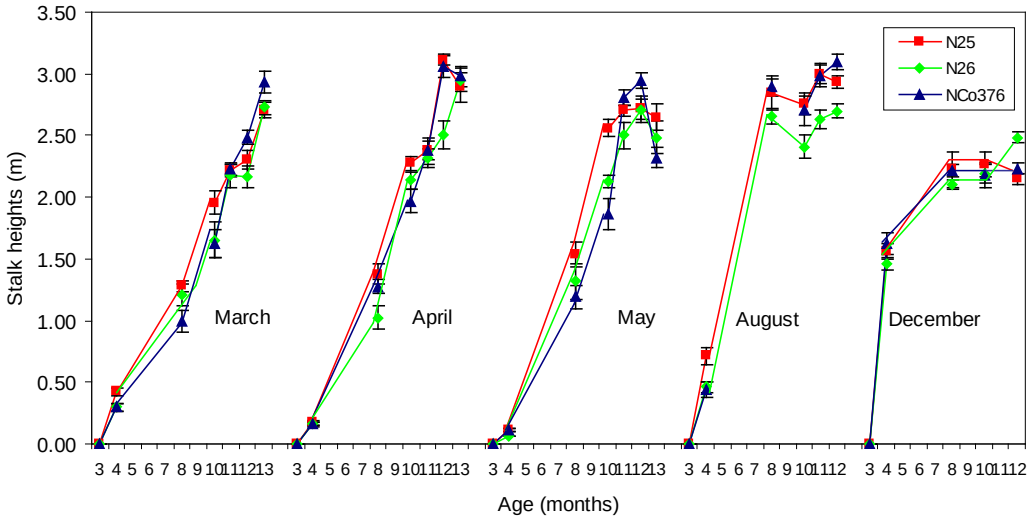


Figure 40 Extension growth of sugarcane stalks measured from the stalk base to the top visible dewlap for cultivars N25, N26 and NCo376 at ages from 3 to 12 and 13 months in March, April, May, August and December ratoon crops. Bars denote standard errors (P=0.05).

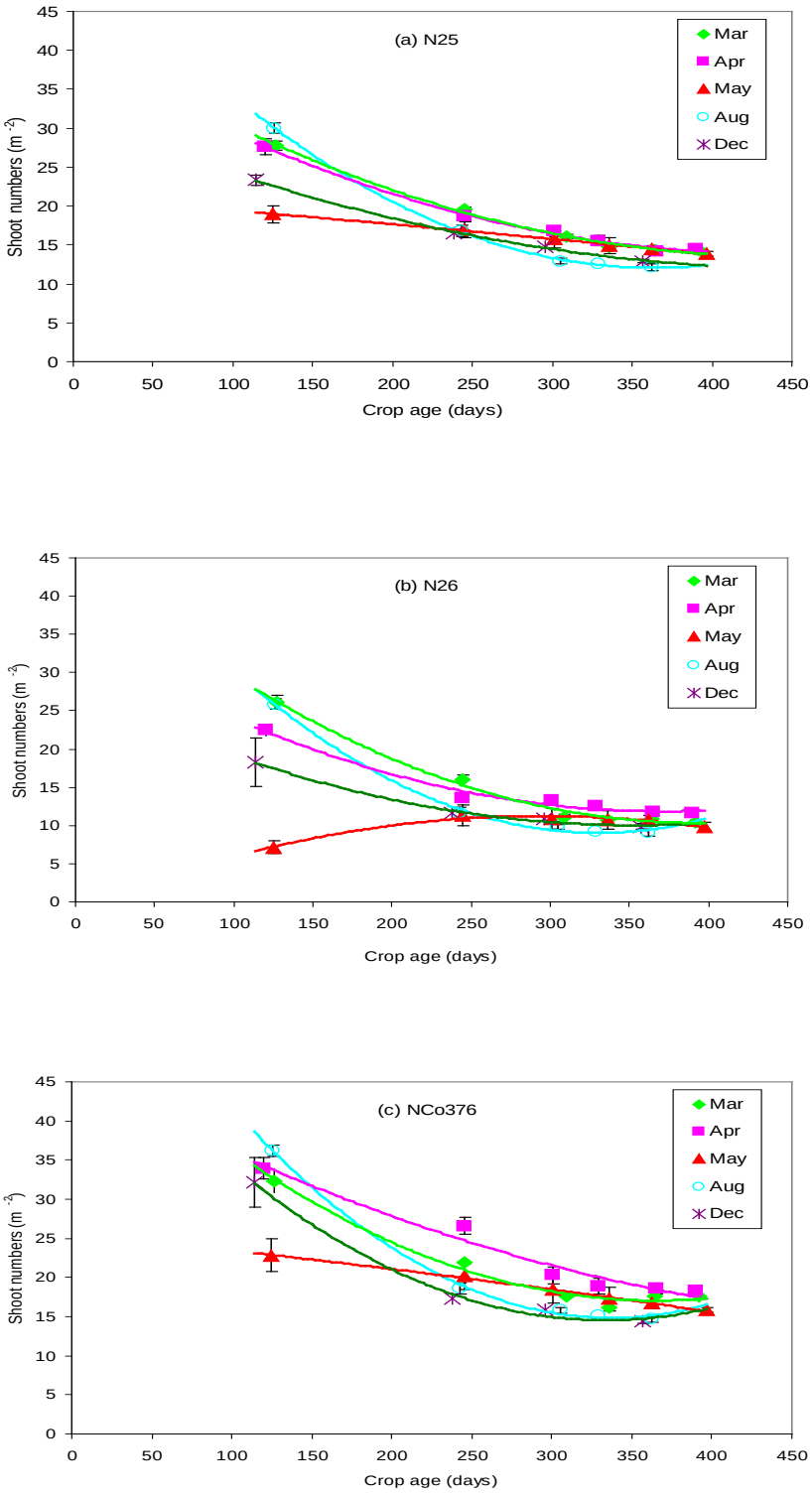


Figure 41 Stalk densities (m^{-2}) of (a) N25, (b) N26 and (c) NCo376 at sample harvesting dates of March. April, May, August and December ratoon crops. Bars denote standard errors (P=0.05).

stalks were, however, on average 0.2 m shorter than the mean cultivar height, except in the December ratoon when the final N26 stalks were 0.3 m taller than the mean height of the three cultivars.

7.2.3 Stalk density during the harvesting period

Shoot densities declined from the earliest sampling dates, at 4 months, through to the final dates for each starting time and all three cultivars. Shoot densities only increased in the N26 May ratoon between 4 and 8 months after which they declined through to the final harvest date. August and December ratoons had significantly (P=0.05) lower stalk densities than March, April and May ratoons when crops were 12 months old (Figure 41, Appendix 2(d)). Similar to what Rostron (1974a) found, winter started crops had lower shoot densities than summer started crops, regardless of crop age. The average stalk densities of N26 (10.5 m^{-2}) at the age of 12 months were significantly lower (P=0.05) than of NCo376 (16.4 m^{-2}).

7.2.4 Stalk fresh mass and dry mass

Stalk fresh mass followed the trends of stalk heights closely (Figures 42 and 40). Stalk fresh mass in a few instances (e.g. NCo376 December and May ratoons) broke the trend by continued increases in later harvests after stalks had reached apparent

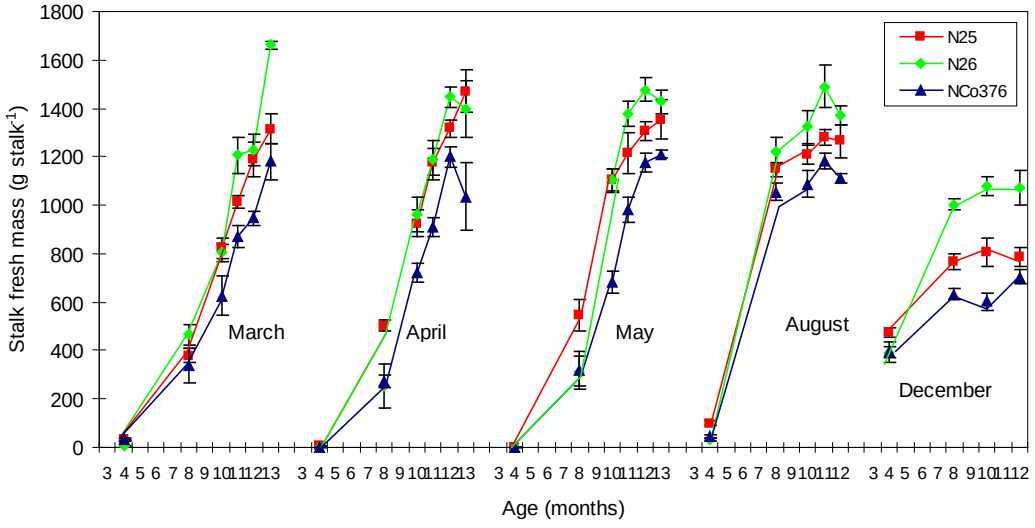


Figure 42 Fresh mass (g $stalk^{-1}$) accumulation of stalks of the sugarcane cultivars N25, N26 and NCo376 in March, April, May, August and December ratoon crops. Bars denote standard errors (P=0.05).

Table 16 Stalk fresh mass (FM), dry mass (DM), dry matter content, fibre mass, sucrose mass, non-sucrose mass and brix mass of N25, N26, NCo376 harvested at the age of 12 months of March, April, May, August and December ratoons.

Cultivar/ Crop start date	Fresh mass g stalk^{-1}	Dry mass g stalk^{-1}	Dry matter content g DM g FM^{-1}	Fibre g stalk^{-1}	Sucrose g stalk^{-1}	Non-sucrose g stalk^{-1}	Brix g stalk^{-1}
NCo376							
Mar	946.9	235.5	0.249	101.3	106.5	27.7	134.2
Apr	1 200.0	273.6	0.228	118.2	121.5	33.9	155.5
May	1 174.9	282.2	0.240	122.6	121.8	37.8	159.6
Aug	1 112.5	317.1	0.285	139.8	152.0	24.6	176.6
Dec	704.6	220.2	0.313	111.0	97.0	12.2	109.2
N25							
Mar	1 188.5	217.8	0.183	117.6	118.3	35.3	153.6
Apr	1 317.2	298.6	0.227	124.4	136.8	37.4	174.2
May	1 306.6	298.0	0.228	117.6	145.0	35.4	180.4
Aug	1 264.0	363.3	0.287	148.8	192.9	21.6	214.6
Dec	786.3	232.4	0.296	105.8	114.8	11.9	126.6
N26							
Mar	1 227.3	338.4	0.276	141.7	169.6	26.9	196.8
Apr	1 446.5	388.8	0.269	158.7	202.8	27.3	230.1
May	1 477.3	378.2	0.256	144.6	190.5	43.1	233.6
Aug	1 373.3	316.6	0.249	143.7	237.1	21.0	228.8
Dec	1 071.5	332.2	0.310	149.3	163.5	19.5	183.1
Means							
Ratoons							
Mar	973.9a	228.6a	0.242a	108.2b	113.2b	24.9a	138.1a
Apr	1321.2b	320.3b	0.241a	133.7ab	153.7a	32.9b	186.6b
May	1319.6b	319.5b	0.241a	128.3ab	152.4a	38.7b	191.2b
Aug	1249.9b	332.3b	0.274a	144.1a	194.0c	22.4a	206.7b
Dec	854.1c	261.6c	0.306a	122.0ab	125.1ab	14.5a	139.6a
Cultivars							
NCo376	1027.8a	265.7b	0.263a	118.6a	119.8a	27.2a	147.0a
N25	1172.5a	282.0b	0.244a	122.8a	141.6b	28.3a	169.9b
N26	1230.4a	331.1a	0.276a	140.6b	179.7c	24.9a	199.8bc
SED(month X cultivar)	125.3	28.6	0.036	12.41	17.36	5.67	19.86
SED (month)	53.1	13.0	0.038	13.49	18.74	6.27	21.48
SED(cultivar)	137.4	31.1	0.023	5.94	9.05	2.02	10.13

Table 17 Differences in cane fresh mass (FM), dry mass, fibre, sucrose, non-sucrose and brix mass per stalk at 13 months old compared with 12 months old stalks of NCo376, N25 and N26 crops started in March, April and May.

Cultivar & Crop start date	Fresh mass g stalk^{-1}	Dry mass g stalk^{-1}	Fibre g stalk^{-1}	Sucrose g stalk^{-1}	Non-sucrose g stalk^{-1}	Brix g stalk^{-1}
NCo376						
Mar	234.3	64.9	33.9	36.9	-5.7	31.2
Apr	-165.1	-4.6	1.2	-3.4	-2.4	-5.7
May	37.0	39.8	17.4	27.7	-5.2	22.5
N25						
Mar	125.1	56.1	38.0	26.4	-8.2	18.1
Apr	153.5	12.5	52.2	49.9	-5.5	44.4
May	47.6	77.4	38.1	42.3	-2.9	39.4
N26						
Mar	433.4	124.2	63.1	63.5	-1.4	62.8
Apr	-49.3	12.5	-1.9	13.7	0.6	14.3
May	-50.5	43.3	20.1	32.5	-9.3	23.2

maximum heights. This was due to stalk dry mass having continued to accumulate after stalk extension growth had ceased. Stalk mass and stalk density could also have increased through increases in stalk girth (Sinclair *et al*., 2005). Dry mass accumulation lagged behind fresh mass in early stages of growth. As crops aged, fresh mass accumulation slowed in relation to dry mass (Figures 42 and 43) so that dry matter content rose from about 0.11 g g^{-1} at 4 months of age to 0.31 g g^{-1} at 12 months of age (Table 16). At 12 months of age August and December ratoons had significantly higher (P=0.05) dry matter content than the March, April and May ratoons (Table 16). The relatively low dry matter content of the N26 August ratoon crop was an exception to this trend. The significantly higher dry mass of N26 (P=0.05), compared with NCo376 and N25 in the March, April and May ratoons was due to significantly higher fresh mass and dry matter content. Fresh mass of NCo376, N25 and N26 of the March, April and May ratoons increased by 35.4, 108.7 and 111.2 g $stalk^{-1}$ between the ages of 12 and 13 months, respectively (Table 17). During the same period dry mass increased by 33.4, 48.7 and 60.0 g $stalk^{-1}$ in NCo376, N25 and N26, respectively. Stalk dry mass increments expressed as g d^{-1} between harvesting dates were largest when March, April and May ratoon crops were between 10 and 12 months old and were substantially higher in N26 than N25

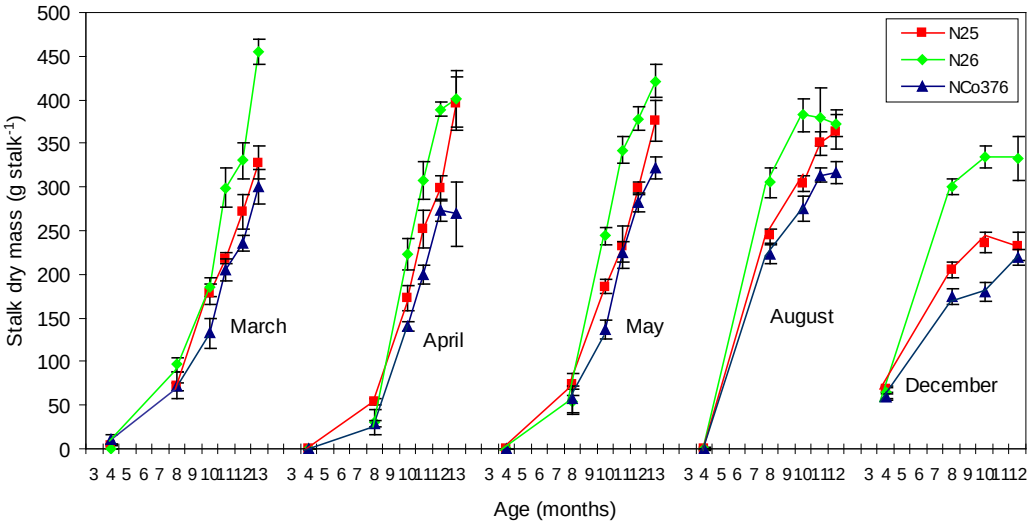


Figure 43 Dry mass (g $stalk^{-1}$) accumulation of sugarcane stalks of the cultivars N25, N26 and NCo376 ratoons started in March, April, May, August and December. Bars denote standard errors (P=0.05).

and NCo376 (Figure 44). The stalk mass increments of the December ratoons were substantially greater after 4 months of age than the increments of crops started at

other times. However, at 8 months of age the growth rates of the August crops were higher than in the December crops. During the period of 4 months to 8 months of age

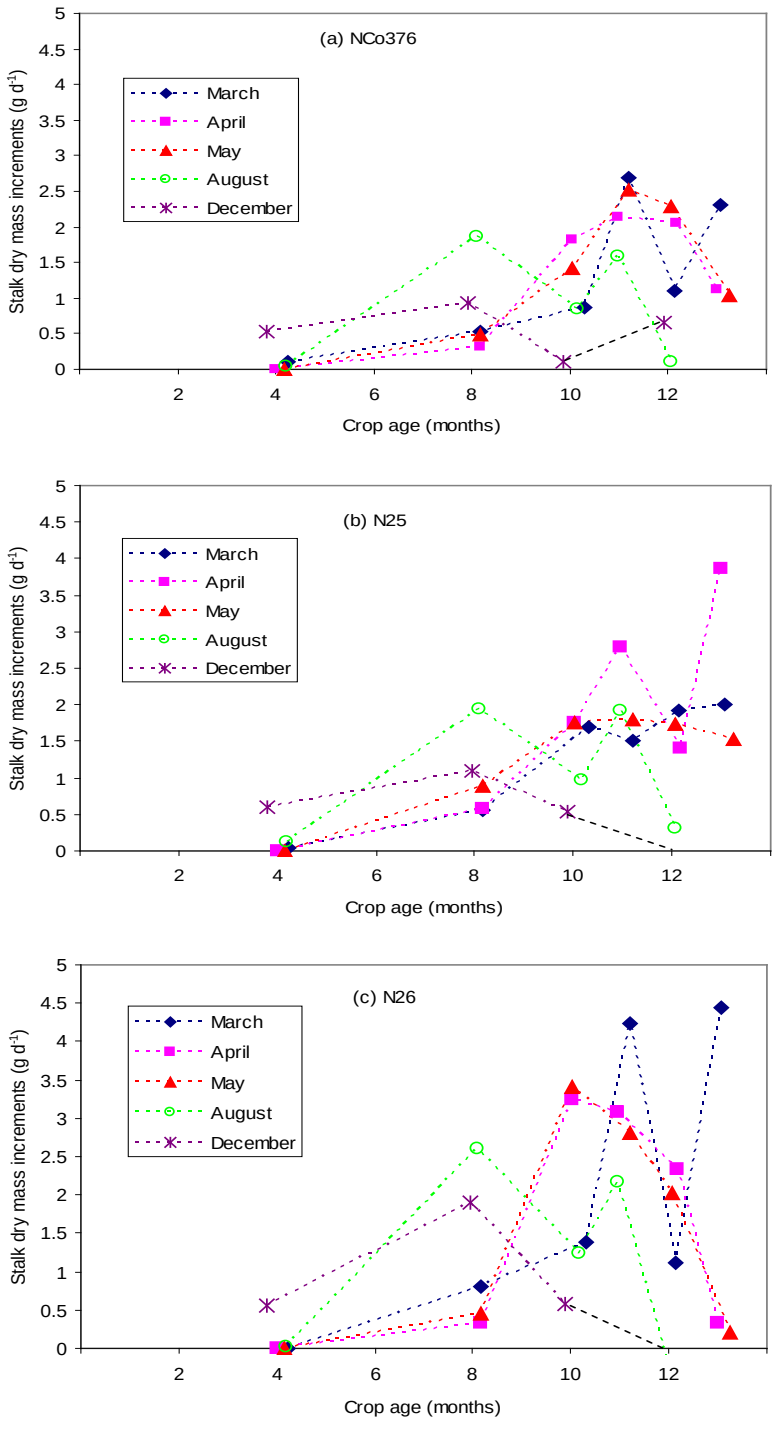


Figure 44 Stalk dry mass increments (g d^{-1}) between 0 - 4, 4 - 8, 8 -10, 10 -11, 11-12 and 12 - 13 months of age of (a) NCo376, (b) N25 and (c) N26 of March, April, May, August and December ratoon crops.

the December ratoon had passed through the period of low temperature and radiation of the months May to August. In contrast, in the period 4 months to 8 months of age the August ratoons experienced the high temperature and radiation of the months December to April. After the age of 10 months in October, the growth rate of NCo376 stalks in the December ratoon crop appeared to increase in response to increasing temperatures during October and November; this higher growth rate after the age of 10 months and after winter was not evident in N25 and N26 (Figure 44).

7.2.5 Stalk fibre and sugars

The water insoluble lignocelluose component of stalks is commonly referred to as fibre. The water soluble components are mainly sucrose, glucose and fructose. Glucose and fructose collectively are referred to as non-sucrose and all the sugars are referred to as brix. Organic components of the stalk such as oligosaccharides and proteins are only present in relatively small amounts (Thompson, 1988).

7.2.5.1 Fibre and sugar dry matter contents (g g^{-1} dry mass)

Generally fibre content rose to a maximum in all except in the December ratoons, during the first 8 months, after which it declined before stabilizing as stalks aged further (Figure 45). In the December ratoons fibre content peaked within 4 months after the crop start date. Similarly, non-sucrose contents rose during early growth and declined thereafter as stalks aged. After having peaked, non-sucrose content then decreased in N25 and NCo376 throughout the sampling periods but reached a stable level before the age of 12 months in the N26 August and December ratoons. Sucrose content rose rapidly during the first 8 months reaching higher levels in March, August and December ratoons than in the April and May ratoons (Figure 45). The maximum sucrose content attained by stalks was successively higher from the March through to the August ratoons when it was 0.53, 0.63 and 0.49 g^{-1}gin N25, N26 and NCo376, respectively. During early growth of December and August ratoons sucrose levels rose to similar levels but then reached a plateau in the December ratoon crops. Sucrose contents rose to levels greater than 0.40 g g^{-1} within 8 months in the March, August and December ratoons and only reached levels greater than 0.40 g g^{-1} after 10 months in April and May ratoons (Figure 45). At the age of 12 months stalks had an overall average sucrose content of 0.49 g g^{-1} ; the gain of 0.09 g g^{-1} during the final 2 months suggest that there was no increase in the rate of sucrose accumulation during the final 2 months of growth.

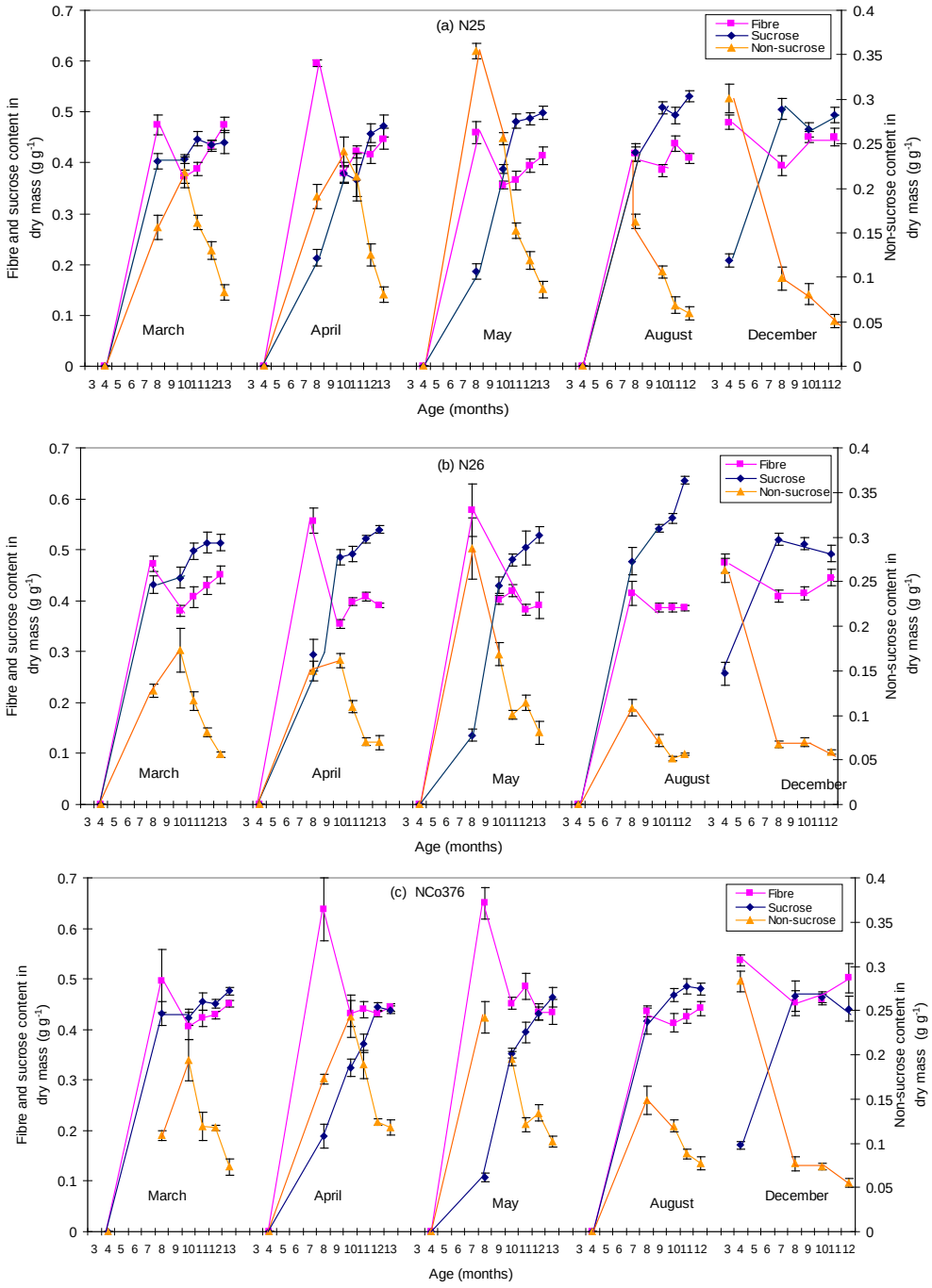


Figure 45 Fibre, sucrose and non-sucrose dry mass content of stalks of the sugarcane cultivars (a) N25 (b) N26 and (c) NCo376 of March, April, May, August and December ratoon crops. Bars denote standard errors (P=0.05).

7.2.5.2 Fibre, non-sucrose and sucrose mass (g stalk⁻¹)

Fibre, non-sucrose (mainly glucose+fructose) and sucrose are the major components of the dry mass of the sugarcane culm. Fibre is the water insoluble component and forms the structure of the culm. Sucrose and non-sucrose, collectively known as brix, are the water soluble components that are mobile or stored in parenchyma vacuoles. The accumulation of these components in relation to each other is depicted in Figure 46.

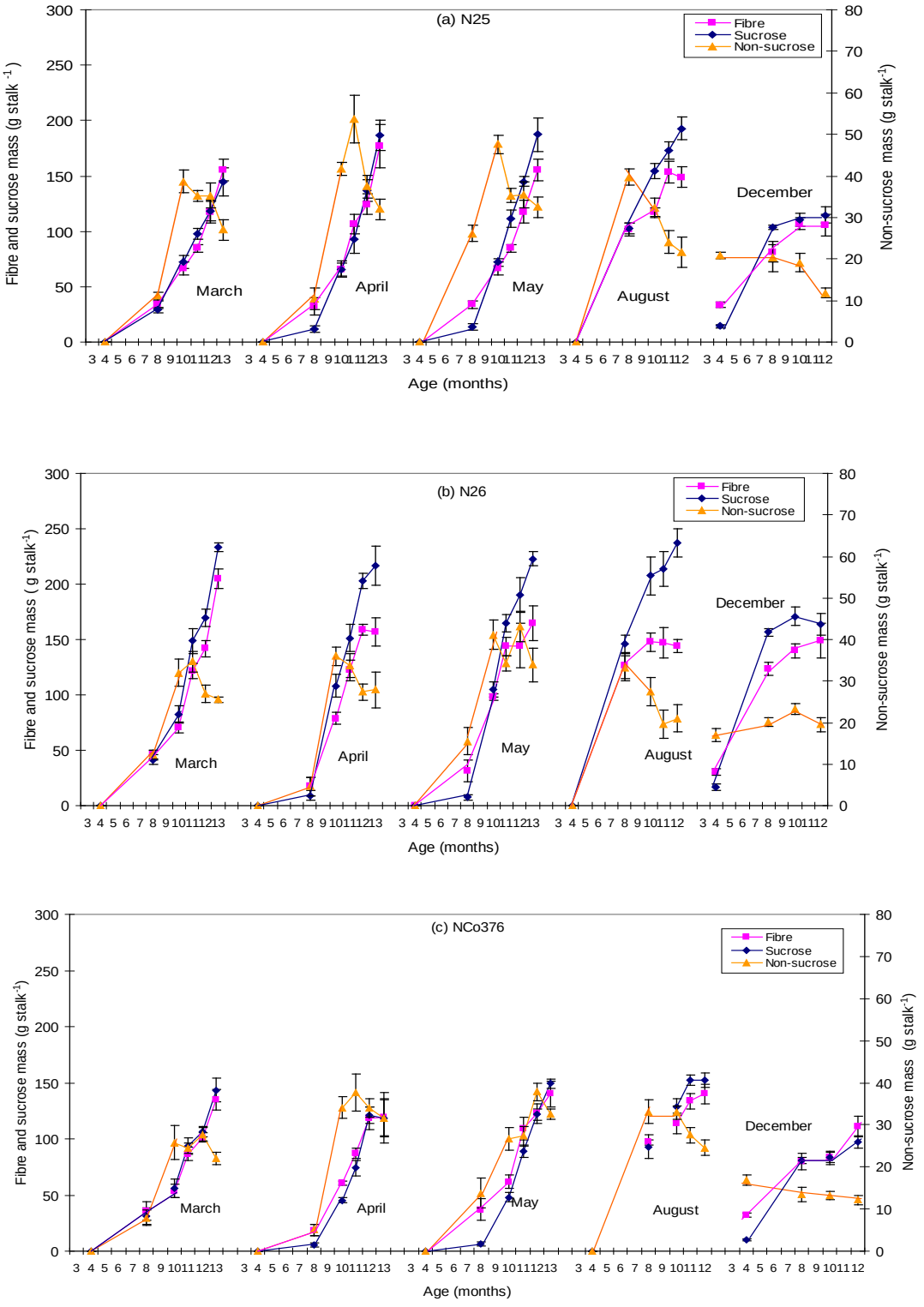


Figure 46 Fibre, sucrose and non-sucrose mass of stalks of the sugarcane cultivars (a) N25 (b) N26 and (c) NCo376 of March, April, May, August and December ratoon crops. Bars denote standard errors (P=0.05).

7.2.5.2.1 Fibre mass

Fibre mass accumulation of N25 followed linear trends in March, April and May ratoons (Figure 46). In August and December ratoons fibre mass peaked before the

final harvest. In N25 fibre mass was the same as sucrose mass in March, April and December ratoons on most harvesting dates. In N26 fibre mass accumulation was linear in the March ratoon only, having either peaked or slowed well before harvest in other ratoons, but particularly in the August ratoons. In NCo376 trends in fibre mass accumulation were linear in March and May ratoons and curvilinear in August and December ratoons and peaked before the final harvest in the April ratoon. Fibre mass of N26 was significantly less than sucrose mass in all ratoons, except the December ratoon. In contrast, sucrose and fibre mass of NCo376 were similar in all ratoons, except the August ratoon. In N26 fibre mass at the final harvest was more than 30% lower than sucrose mass in the April, May and August ratoons.

7.2.5.2.2 Non-sucrose mass

Maximum non-sucrose mass per stalk tended to be lower in August ratoons and was more than 50% lower in December than in the March and April ratoons (Figure 46). In general, non-sucrose mass increased rapidly in young stalks but then slowed as stalks aged and thereafter non-sucrose mass declined. The decline of non-sucrose mass occurred earlier in the August (8 months old) and December ratoons (4 months old) than in the March, April and May ratoons. Exceptions to these trends were the late decline on non-sucrose mass of the NCo376 May ratoon (at 12 months) and in the N26 December ratoon (at 10 months).

7.2.5.2.3 Sucrose mass

The accumulation of sucrose was nearly linear throughout the sampling periods of March, April and May ratoons, only showing a possible peak in the NCo376 April crop at 12 months (Figure 46). In contrast, the rate at which sucrose was accumulated in August ratoons slowed after 8 months and peaked at 11 months of age. The accumulation rate slowed more severely in December than in the August ratoons so that sucrose mass was significantly lower than in the August, May and April ratoons. March ratoons produced similar sucrose yields per stalk as December ratoon crops. All March and December ratoons yielded significantly less sucrose per stalk at the age of 12 months than the April, May and August ratoons. August ratoons yielded significantly more sucrose per stalk than all other crops at the age of 12 months. The mean sucrose mass accumulated at the age of 12 months were 142, 193 and 120 (g $stalk^{-1}$) for N25, N26 and NCo376, respectively (Table 16). On average, sucrose mass of NCo376, N25 and N26 increased by 20.4 (17.5%), 45.3 (36.5%) and 36.3 (19.3%) g $stalk^{-1}$, respectively between the ages of 12 and 13 months (Table 17).

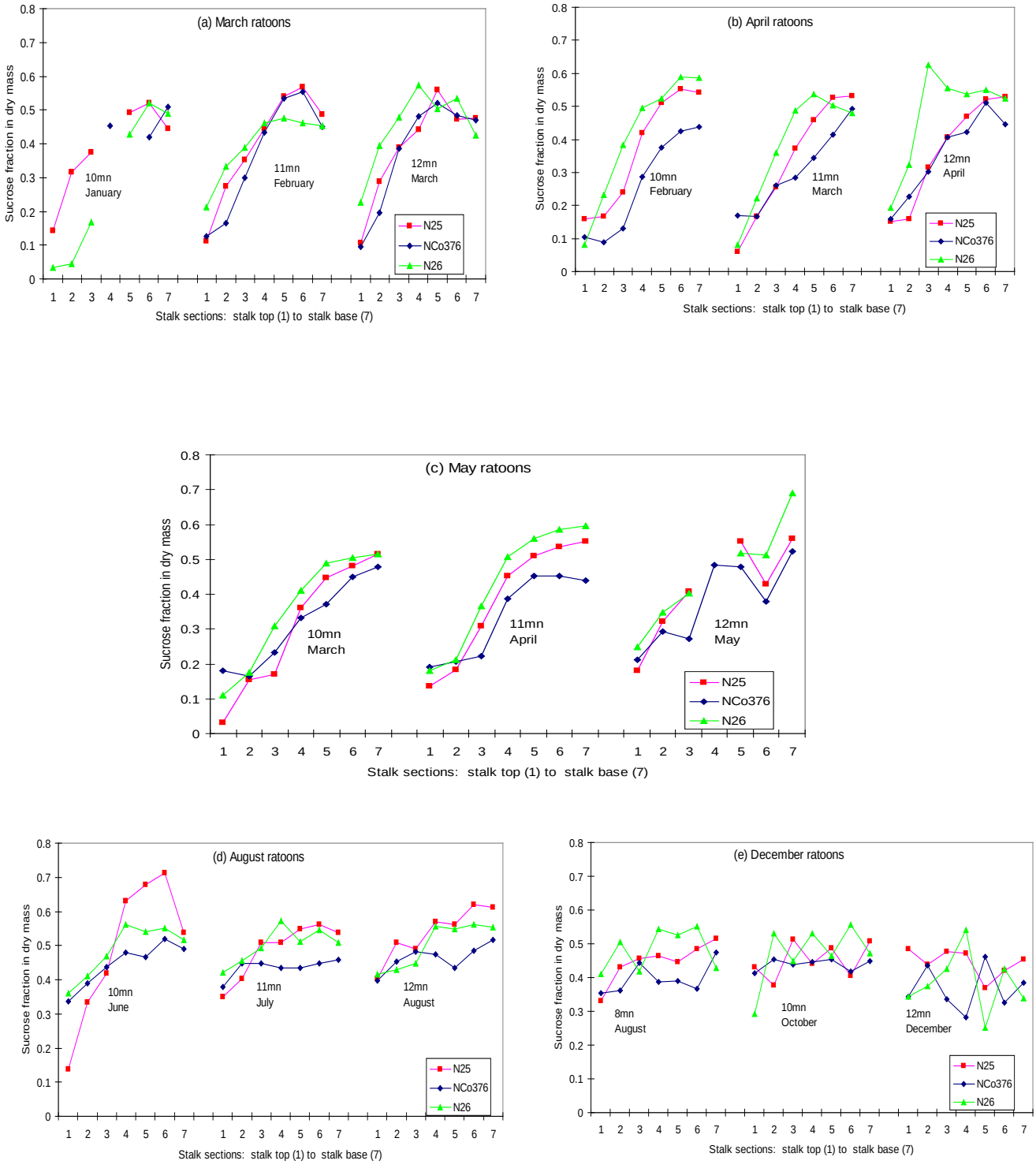


Figure 47 Sucrose content in dry mass (g sucrose g dry mass^{-1}) of stalk sections from top (section 1) to the base (section 7) from stalks 10, 11 and 12 months old (and months of harvesting) of N25, NCo376 and N26 of (a) March, (b) April, (c) May, (d) August and (e) December ratoon crops.

7.2.6 Sucrose fractions in stalk sections of crops as they aged

Generally, sucrose concentrations increased from less than 0.2 g sucrose g dry mass^{-1} in the most distal sections (1) to about 0.5 g sucrose g dry mass^{-1} in the basal sections (5, 6 and 7) of the stalks in March, April and May ratoons. This steep gradient in sucrose concentrations along the stalks was less in August and December ratoons because sucrose concentrations of distal sections were mostly above 0.3 g sucrose dry mass^{-1}. Also, in the December ratoons the maximum sucrose concentrations in the basal sections was not much higher than 0.5 g sucrose dry mass^{-1} while basal sections of other ratoons were generally well above 0.5g sucrose dry mass^{-1}. The cultivar N26 had the highest sucrose concentrations in most stalk sections of March, April and May ratoons of 12-month old stalks. This was true for N25 in the August and December ratoons. The sucrose fractions in the basal stalk sections (Figures 47 and 48) differed little between the ages of 10 and 12 months, in comparison with the large increases in sucrose concentrations in the distal sections between the ages of 10 to 12 months. There was a tendency for greater portions of the stalk to accumulate the apparent maximum sucrose concentrations as the stalks aged, as seen in the August ratoons (Figure 47).

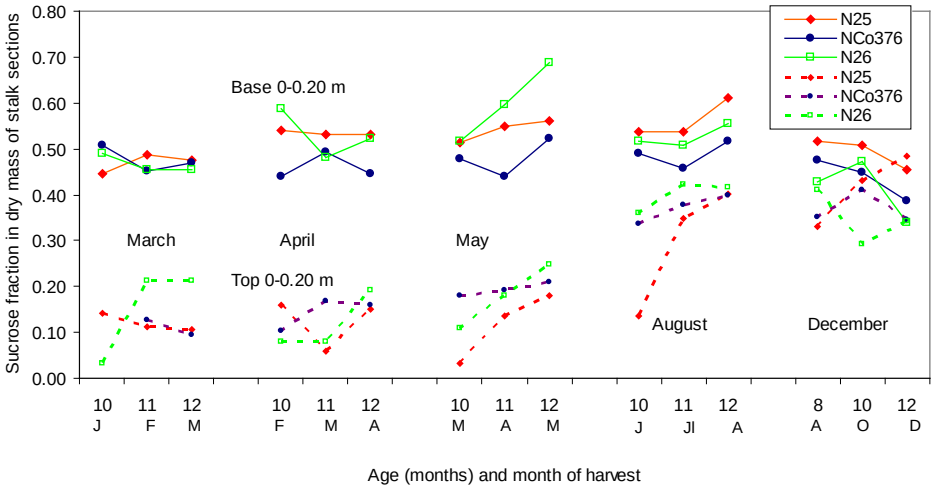


Figure 48 Sucrose concentrations (g sucrose g dry mass^{-1}) in sections from the base (0-0.20 m) (solid lines) and from the top (0-0.20 m) (dashed lines) of stalks harvested at 10, 11 and 12 months of age (with months of harvest) of March, April, May, August and December ratoons for the cultivars N25, N26 and NCo376.

The flat gradients of sucrose concentrations of 11-month old stalks in the August ratoon were similar to that in the 8-month old December ratoons. At 8 months of age the sucrose content in the top 0.20 m sections were 0.33, 0.35 and 0.41 g sucrose

g^{-1} dry mass in N25, NCo376 and N26 of December ratoons, respectively. Such levels were only approached in the top section of May ratoons when they were 13 months old (data not shown). If the steepness of the gradient i.e. the difference in sucrose fractions of the top and bottom stalk sections, is an indication of the crops sink capacity then clearly the December ratoon crops had little sink capacity after 8 months. In contrast, the steep gradients of sucrose fractions in stalk sections of the March, April and May ratoons suggest they had potentially large sink capacities up to the age of 12 months. This may be the reason for the large increases in sucrose content in response to chemicals that are applied as ripeners to autumn/winter harvested crops and the poor responses that are typical of late season ripening (Donaldson, 1999; Leibbrandt, 1989). The basal and distal 0.20 m sections of stalks harvested at the ages of 10, 11 and 12 months were compared to further reveal the effects of season and age on the sucrose fractions in the stalks of N25, N26 and NCo376 (Figure 48).

Lodging was severe after the age of 10 months in December ratoons so that access to plots was not possible without causing damage to the crop and samples were therefore not harvested from the December ratoons when they were 11 months old (Appendix 1 (c)). Early stalk growth was rapid in the December ratoons and stalk mass at 8 months was comparable to that of 10-month old stalks of March, April and May ratoons (Figure 43). The consistently high sucrose concentrations in the basal sections of the March and April ratoons suggested that sucrose was not being accumulated in the stalk bases during the period between 11 and 12 months of age. During this period sucrose fractions were higher in the basal sections of the May and August ratoons and were lower in the December ratoons. These trends were more pronounced in N26 and N25 than in NCo376 and suggest that sucrose concentrations in the stalk base were reflecting seasonal trends. The sucrose concentrations in the top sections were mostly highest in N26 and lowest in N25 at 12 months of age. The exception was in the December ratoons in which the N25 tops had the highest sucrose concentrations (Figures 48). When sucrose concentrations in the base and top sections from stalks that were between 10 and 12 months old were plotted against the month during which they were harvested, seasonal trends became more evident (Figure 49). Sucrose concentrations in the top section of the stalk increased linearly (R^2>0.60) from January to December (Figure 49). There was a decrease in the sucrose concentration in the top sections of December ratoons in N26 and NCo376 which was not evident in N25 distal sections. The relationships between sucrose concentrations in basal stalk sections and time of year of

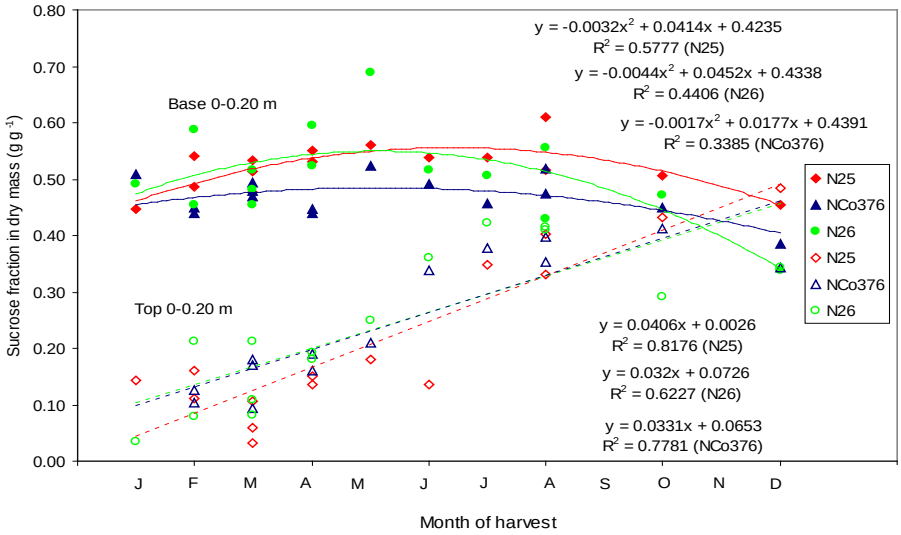


Figure 49 Sucrose concentrations in dry mass (g g^{-1}) of the top 0-0.20 m and basal 0-0.20 m sections of stalks (10, 11 and 12 months old) from N25, N26 and NCo376 stalks harvested throughout the year. When the data for the December ratoon were excluded the R^2 values of N26 and NCo376 were increased (R^2>0.84) and decreased for N25 (R^2 = 0.58).

harvesting were curvilinear (R^2>0.33) and was higher from January through to August and then was lower in December in N25 and NCo376 stalks. Sucrose concentrations in the base of N26 stalks peaked in May.

7.2.7 Maximum sucrose concentrations

Sucrose concentrations in the base of NCo376 stalks were reported by Inman-Bamber *et al.,* (2002) to be lowest in April ratoons, were high in August and were again lower in December. Seasonal trends were evident when the mean sucrose concentration of the lowest 0.40 m basal stalk sections of N25 and NCo376 were plotted against the month of harvest when stalks were 12 months old (Figure 50). However, sucrose concentrations of N26 were highest in May, while it was highest in August ratoons of N25 and NCo376. Thus N26 accumulated maximum sucrose concentrations earlier than did NCo376 and N25 when temperatures were relatively high. The lower sucrose levels in the stalk base of the December ratoon (Figure 50) could have been the result of sucrose was being remobilized from the base of the stalk to support renewed growth of the distal stalk sections after winter (Inman-Bamber *et al*., 2002). The data presented in Figures 42 to 45 for the December ratoon crop suggest that there was little stalk growth, but rather growth was as new foliage, after the age of 8 months. December ratoon crops began lodging on about 4

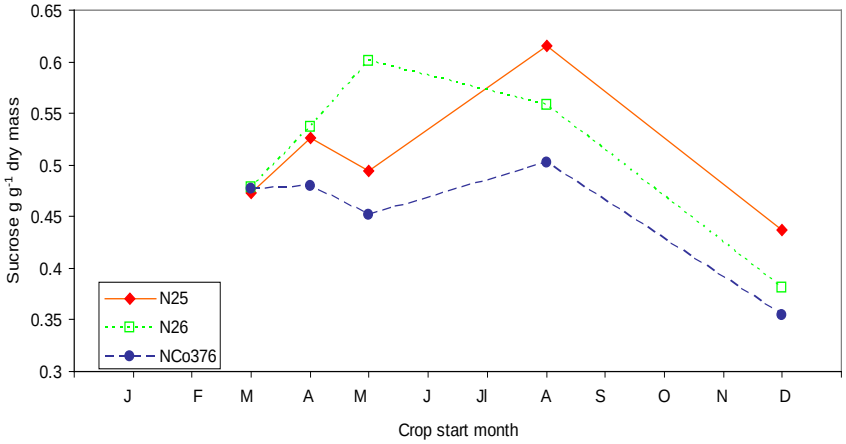


Figure 50 Averaged sucrose concentrations (g g^{-1} dry mass) in two bottom sections (combined 0-0.20 m and 0.20-0.40 m from the stalk base) of 12-month old stalks of N25, N26 and NCo376 March, April, May, August and December ratoon crops. Each point is the mean of two sections from 30 stalks.

June 1999 (6 months old) when stalks were blown over during wet and windy conditions, but extensive lodging only occurred after the age of 10 months. Only erect stalks were harvested until the age of 10 months. The reason for the variability in sucrose concentrations between stalk sections in the December ratoons (Figure 47) is therefore unlikely to have been due to lodging *per se*, except when the crops were 12 months old. The means of the sucrose concentrations in the bottom two sections from the five ratoon dates suggest that N25 and N26 had higher capacities to store sucrose (0.61 and 0.60 g^{-1}gdry mass , respectively) compared with the lower capacity of NCo376 (0.50 g g^{-1} dry mass). The value for NCo376 was slightly lower than the 0.55 g g^{-1} dry mass determined for NCo376 in an experiment at La Mercy, RSA that was not irrigated (Inman-Bamber *et al.*, 2002). The highest whole stalk sucrose values at 12 months age (Figure 45) were 0.48 g g^{-1} for NCo376 and 0.53 g g^{-1} for N25 in the August ratoons. The cultivar N26 produced its highest whole stalk sucrose concentration (0.52 g g^{-1}) in the April ratoon. The capacity of the whole stalk to store sucrose was therefore higher in N25 and N26 than in NCo376 and they were at the higher end of the maximum range for sugarcane (0.45-0.55 g g^{-1}) proposed by Muchow, Robertson, Wood & Keating, (1997b).

7.2.8 Sucrose mass accumulation relative to shoot foliage and stalk fibre

7.2.8.1 Sucrose vs shoot foliage estimates

Polynomial functions were fitted to sucrose and shoot total foliage mass data of NCo376, N25 and N26 when crops were 8 and 12 months old to investigate how sucrose and shoot foliage were affected by season. The effect of season on foliage and sucrose mass was more evident when crops were 8 months old (Figure 51).

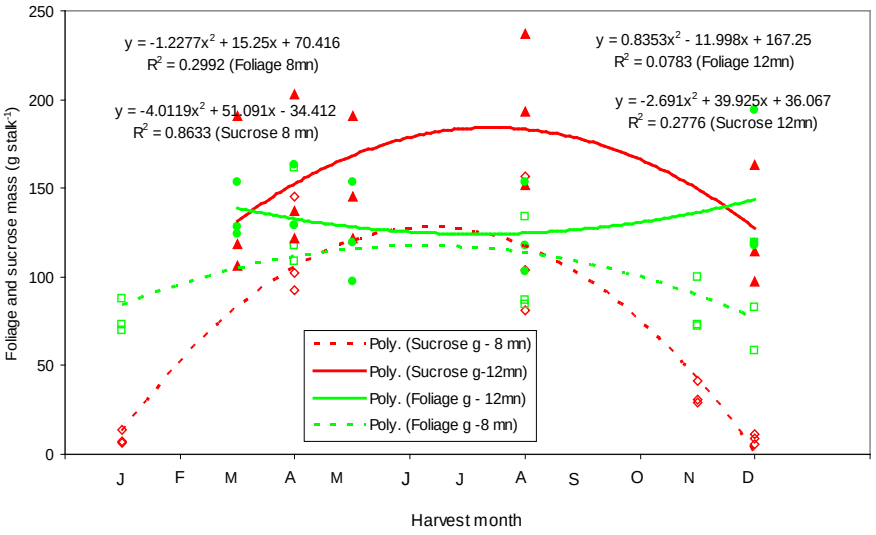


Figure 51 Generalised trends of shoot foliage and sucrose mass (g stalk^{-1}) of 8 - month old and 12-month old crops of NCo376, N25 and N26 March, April, May, August and December ratoon crops.

Eight month old crops harvested between May and September had higher stalk sucrose mass than any other harvest month. These stalks started growth between November and January and experienced high daily temperatures and high solar radiation flux during emergence and for much of the 8 month period. The lowest stalk sucrose mass was from stalks harvested in January and December and they were associated with relatively high foliage mass. These crops had started growth in May and April, respectively, and had experienced cooler winter temperatures and lower daily solar radiation flux during germination, emergence and early canopy development. At 12 months of age sucrose mass was higher than at the age of 8 months, but the trends in the two age groups were similar; winter harvested crops produced the highest sucrose mass and March and December crops produced the lowest sucrose mass. Foliage mass, however, except for the slight decline through winter months, varied little through the season. Singels & Inman-Bamber (2002) and Singels *et al*. (2005a) showed that sucrose continued to accumulate in stalks when foliage growth was severely restricted during winter (minimum temperatures < 15°C). The relationship between stalk sucrose and stalk fibre was investigated by considering the relationship between stalk sucrose mass and stalk fibre mass of NCo376, N25 and N26 crops started in March, April, May, August and December. Sucrose mass and stalk fibre mass of NCo376 tended to increase by similar amounts, except for the crop started in April in which sucrose mass accumulation generally lagged behind fibre mass (Figure 52). In contrast, sucrose mass tended to increase more than fibre mass in N25 and particularly in N26 when fibre mass

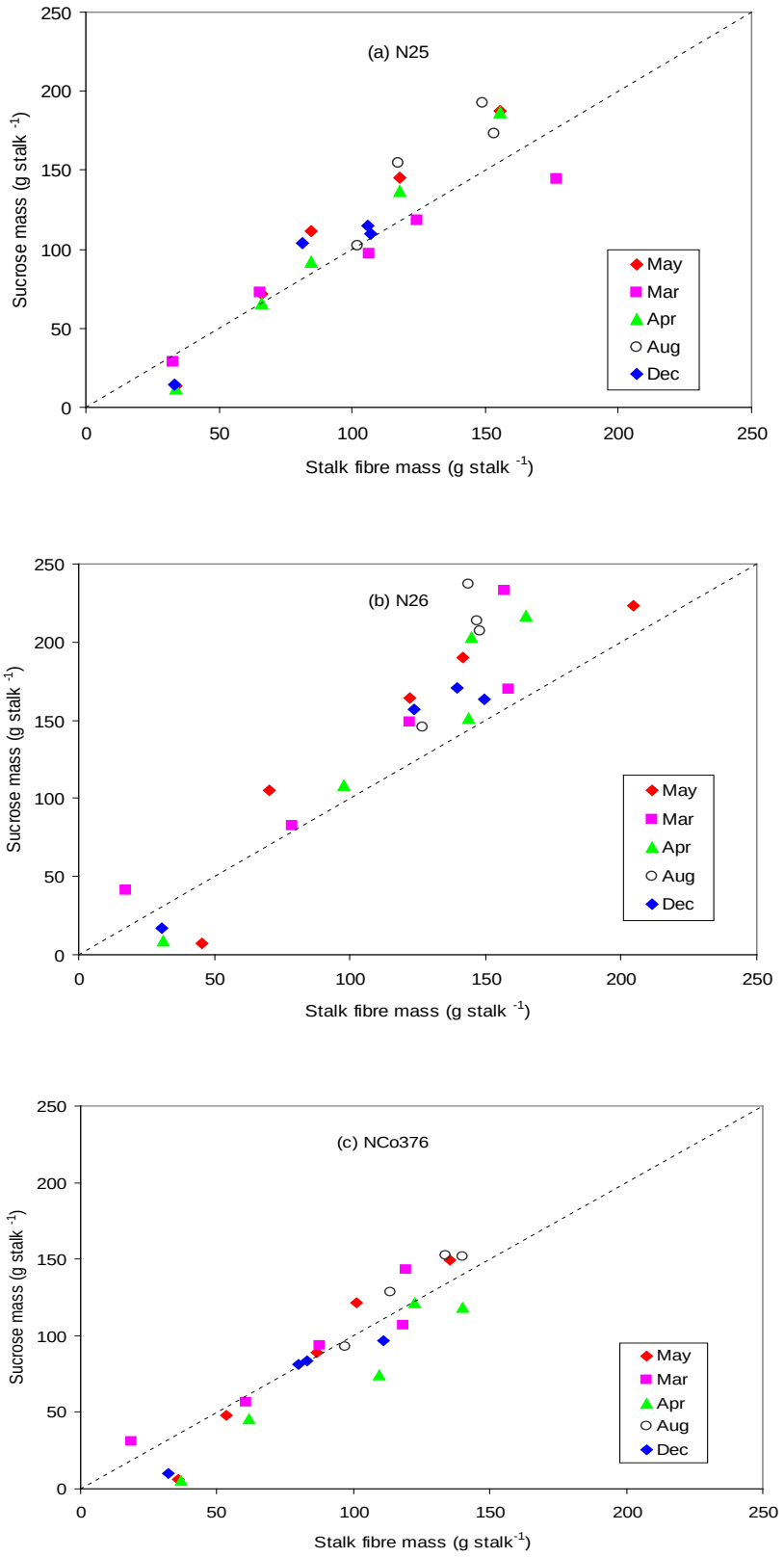


Figure 52 Sucrose mass relative to stalk fibre mass (g stalk^{-1}) of (a) N25, (b) N26 and (c) NCo376 in March, April, May, August and December ratoon crops.

7.2.8.2 Sucrose vs stalk fibre

exceeded 125 g stalk⁻¹. The clear exception was the lower rate of sucrose mass accumulation compared with fibre mass when fibre mass was greater than 125 g stalk⁻¹ of the N25 March ratoon crop.

7.2.9 Foliage mass, stalk mass, fibre mass and sucrose mass vs thermal time

The cumulative dry mass, fibre mass, sucrose mass and stalk heights were plotted against cumulative thermal time calculated from temperatures ranging from 0 to 20°C, by one unit increases. The data from December ratoons were excluded from the analysis because plants did not respond as expected to increasing temperatures and higher daily solar radiation fluxes after winter. By iteration the most appropriate base temperature for each parameter was taken as that with the highest R^2 value (Table 18, Figure 53). The relationships between sucrose mass (g stalk⁻¹) and

Table 18 Base temperatures (base T, °C) and R^2 values (all significant P=0.05) of a linear fit between stalk foliage, dry stalk mass (DM), stalk fibre and sucrose and cumulative thermal time from crop start date. Highest R^2 values are shown from regressing on cumulative thermal time using base temperatures from 0 to 20°C.

Cultivar		Foliage g stalk⁻¹	DM g stalk⁻¹	Fibre g stalk⁻¹	Sucrose g stalk⁻¹
N25	base T	12	20	16	16
	R^2	0.883	0.901	0.895	0.914
N26	base T	14	20	19	19
	R^2	0.848	0.926	0.959	0.958
NCo376	base T	14	20	17	17
	R^2	0.891	0.921	0.960	0.925

cumulative thermal time using base temperatures of 16, 17 and 19°C for N25, NCo376 and N26, respectively were assessed (Figure 53). More than 88% of the variation in these parameters was accounted for by temperature. Seasonal differences in the growth of stalks reflected by the way they elongated, accumulated dry mass, sucrose mass and fibre mass were less evident when they were plotted against cumulative thermal units (°C d). Cumulative thermal time could therefore be used to describe the mass of the components of N25, N26 and NCo376 with reasonable accuracy for March, April, May and August ratoons, but not for December ratoons. The analysis suggests that N25 will continue to produce foliage and stalk fibre at lower temperatures than N26 and also NCo376, but to a lesser extent. Similar differences in base temperatures required for canopy development were reported for these cultivars by Singels & Donaldson (2000). They showed that the canopy development of N26 was best described using a base temperature of 17°C while N25 and NCo376 required 16°C. Sucrose mass accumulated by N26 stalks

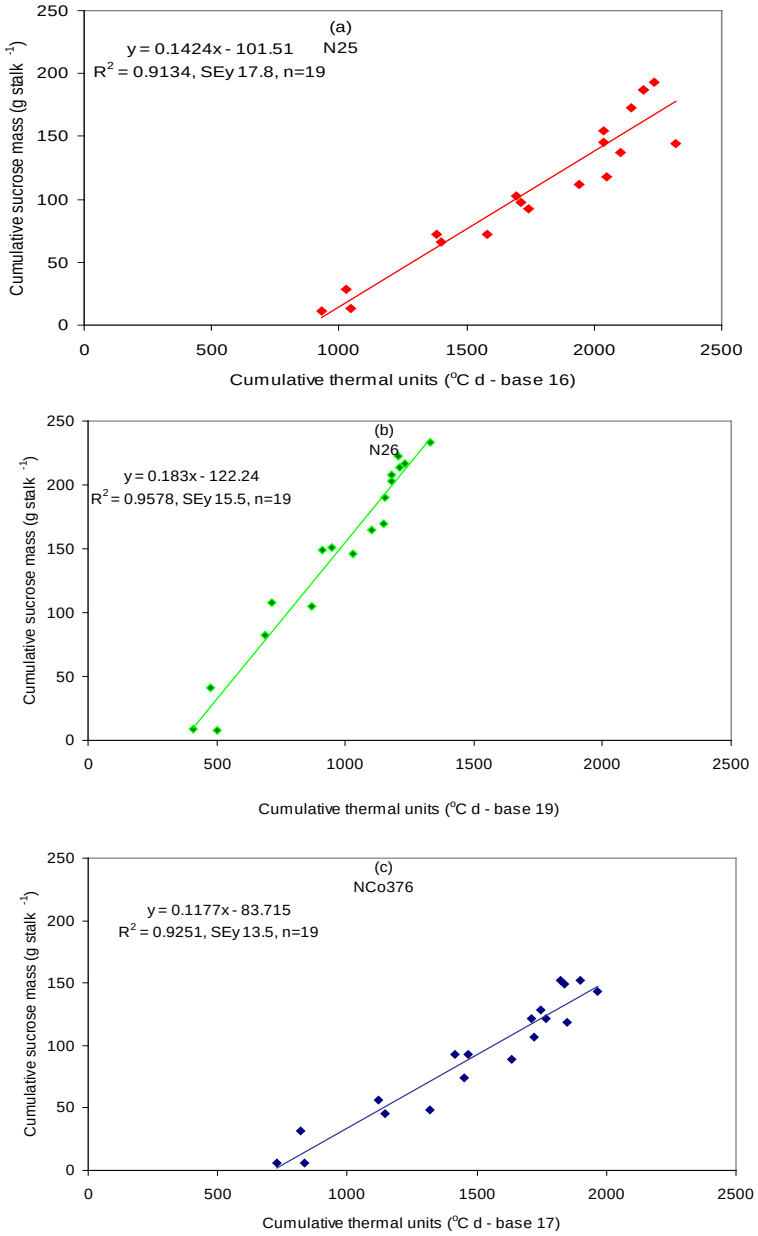


Figure 53 Sucrose mass (g stalk⁻¹) regressed on cumulative thermal time using base temperatures of 16°C for (a) N25, 19°C for (b) N26 and 17°C for (c) NCo376. Linear equations, R² values, SEy and number of observations (n) are shown in the graphs.

when they were 12 months old was significantly higher than that by N25 and NCo376 (Figure 53). Given that mass accumulation is largely a function of intercepted radiation to which temperature is related in a local sense, the above described associations will have very limited use.

7.3 Concluding Discussion

Stalks first appeared above-ground level when shoots had nine leaves and this is similar to findings in an Australian study. However, the timing of stalk appearance

needs further verification under conditions in South Africa. There is good evidence to show that several growth process and sucrose accumulation in particular, either start at, or require, higher temperatures in N26 than in N25 and NCo376.

Growth of sugarcane stalks was affected by crop start date such that dry mass and sucrose yields per stalk of March and December ratoons were significantly lower than in April, May and August ratoons. August ratoons yielded significantly more sucrose and dry mass per stalk than the other ratoons in this study. On average stalks of August and December ratoons had significantly higher dry matter content than March, April and May ratoons. The stalks of N26 were heavier and yielded significantly more sucrose than those of NCo376 and N25. August and December ratoons had significantly lower shoot densities than March, April and May ratoons. Final average shoot densities were significantly higher in NCo376 than in N26 (Appendix 2 (d)). Higher stalk sucrose yields during winter and spring months were associated with lower foliage mass and lower stalk fibre mass in older stalks. The poor yields of December ratoons were associated with a marked reduction in the rate of dry mass accumulation after the crop was 8 months old. The top part of the stalk of the 8-month old December ratoon had significantly higher sucrose content than the other ratoons. The poor growth response in the December crop to increasing temperatures and higher solar radiation after winter was unexpected. It is proposed that when growth slowed in winter high sucrose concentrations accumulated in the leaves and top part of the stalks. High sucrose levels may then have inhibited photosynthesis (Mc Cormick *et al*., 2006) so that the crop became moribund and growth was dampened when temperatures rose in spring and summer. Lodging started early in the December ratoons and may have exacerbated the recovery to more rapid growth but it is not considered to be the underlying reason for the lack of vigour in the later spring and summer period of the December ratoons. The cultivars N22 and NCo376, which did not lodge, were reported to have grown very slowly during spring and summer of a December ratoon crop of the present study (Donaldson *et al*., 2008a). When March, April and May ratoons were harvested at 13 months of age stalk sucrose yields were increased substantially above those in 12-month old crops.

CHAPTER 8

ANNUAL YIELDS

8.1 Introduction

Sugarcane crops that are irrigated are mostly harvested after 12 months of growth (annually) in South Africa and in many other countries like Swaziland, Malawi, Tanzania, Sudan and Australia. Productivity of farms is measured on annual yields and this facilitates the ease of comparisons between mill areas and across countries. Cane (fresh mass) yield plays a fundamental role in the economics of harvesting and of transporting of sugarcane from fields to mills. It should be noted that annual (as in the title above and elsewhere) refers to crops that are 12 months old. Crop yield is the product of stalk mass, presented in Chapter 7 and stalk densities, presented in Chapter 3. Stalk mass and stalk densities respond differently to the variation in the environment over time, so that trends in average stalk mass data may not reflect changes in crop yields over time. In sugarcane high stalk mass is often associated with low stalk densities and the converse could also be true. Crop yields can therefore not be assumed to follow the trends of mass per stalk and need to be calculated from stalk mass and stalk densities. Stalk dry matter yields can be calculated by the sum of fibre and brix (all sugars) yields. The foliar component of the crop was dealt with in Chapter 6. In this chapter fibre, non-sucrose and sucrose yields are investigated in relation to biomass of 12-month old crops.

8.2 Results and Discussion

8.2.1 Cane fresh mass

In this project, cane yields ranged from 10 162 to 22 268 g m^{-2} for the N25 December ratoon and the NCo376 April ratoon, respectively. There was thus a 54% difference in the highest and lowest fresh cane yields across the five starting times and three cultivars (Table 19). When the March, April and May ratoons were harvested at the

Table 19 Cane fresh mass yields (g m^{-2}) of N25, N26 and NCo376 at the age of 12 months in March, April, May, August and December ratoons.

Cultivar/crop start month	March	April	May	Aug	Dec	Mean
N25	17 076	18 600	18 990	15 347	10 162	16031b
N26	13 428	16 917	15 859	12 411	10 639	13851c
NCo376	16 626	22 268	19 594	16 397	10 177	17013a
Mean	15 710c	19 262a	18 151b	14718c	10 326d	15632
SE	505.4					273.3
LSD (0.05)	1084.2					586.3

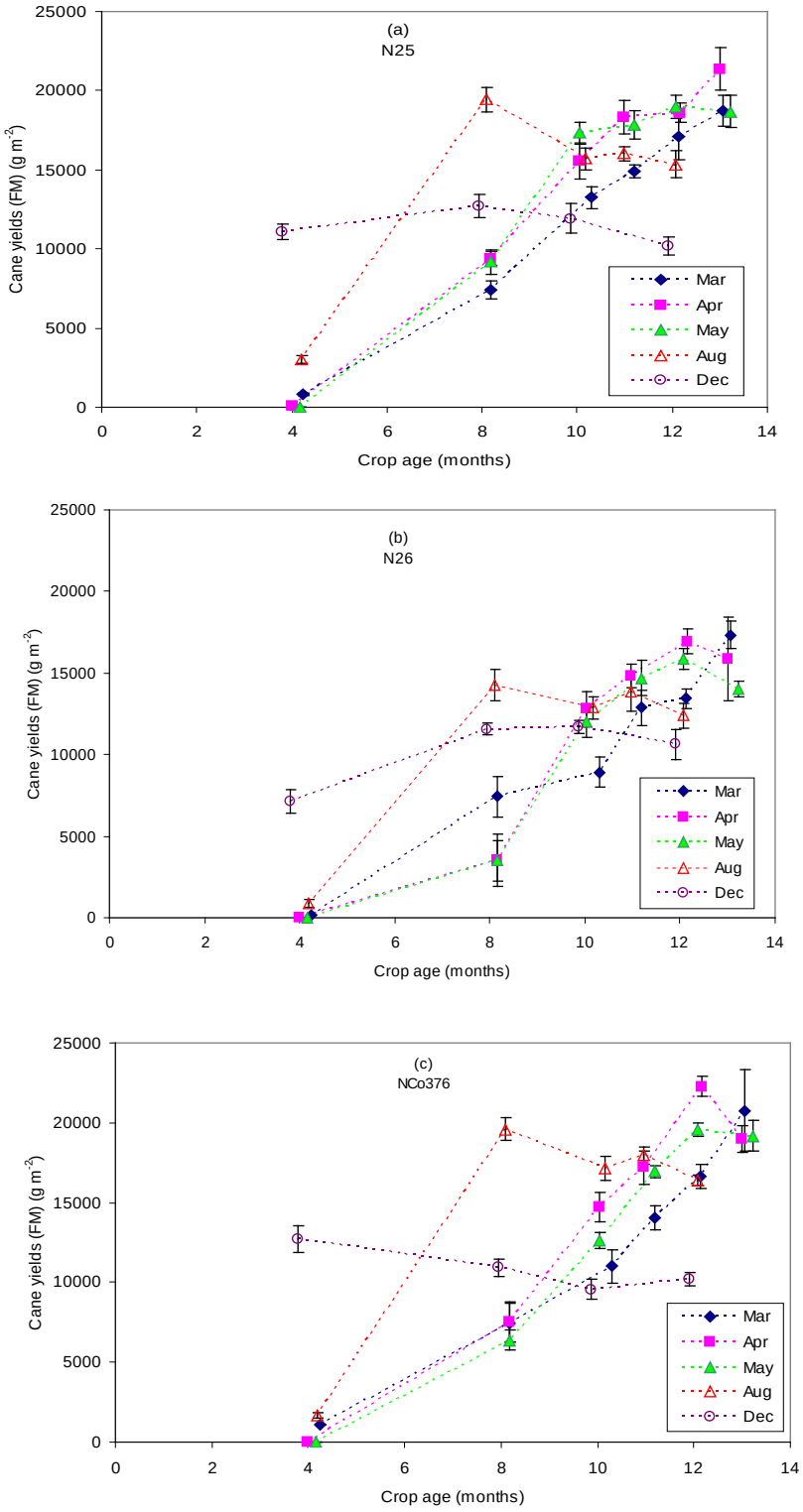


Figure 54 Cane fresh mass (FM) yields of (a) N25, (b) N26 and (c) NCo376 crops started in March, April, May, August and December. Bars denote standard errors (P=0.05).

age of 13 months cane fresh mass yields had increased on average by 20.6 and 2.2 % in the March and April ratoons, but they were not increased in the May ratoons (Table 20). The trends in the cumulative cane yields (Figure 54) for the March, April and May ratoons were linear and were curvilinear for the August and December ratoons. The August and December ratoons produced relatively high cane yields during early growth, particularly in the December ratoon, and then increased only

Table 20 Cane fresh mass yields (g m^{-2}) at the age of 13 months of N25, N26 and NCo376 crops ratooned in March, April and May.

Cultivar/crop start month	March	April	May	Means
N25	18 731	21 355	18 686	19 591b
N26	17 347	15 891	14 023	15 753c
NCo376	20 741	21 838	19 188	20 589a
Mean	18 939a	19 695a	17 299b	18 648
SE		426.2		312.7
LSD (0.05)		914.0		670.8

slightly before decreasing during the final months. In contrast March, April and May ratoons initially produced less cane mass and after a slow start maintained a more constant rate of production through to the final harvesting at 13 months (Figure 54). The cane yields at 12 months of age of the August ratoons matched those of the March ratoons. The March ratoons initially developed slower and the August ratoons yielded substantially better than the March ratoons at the age of 8 months. The declining yields after the age of 8 months in the August ratoons were solely due to loss in stalk density (Figure 41) since average stalk mass increased throughout the sampling period to the age of 12 months. December and August ratoons exhibited slower growth rates when they were about 4 and 8 months old, respectively. Cane yields started to decrease in the December ratoon of NCo376 after 4 months of growth. At the onset of the slower growth rates in the August and December ratoons daily minimum temperatures had dropped to less than 18°C, maximum daily temperatures were declining but were still above 30°C, day lengths had shortened to 11.5 hours and daily radiation flux was about 20 MJm^{-2} d^{-1} in April. The declining stalk densities of the December ratoon towards the final harvest date caused cane yields to be on average 46% (8 936 g m^{-2}) lower than the high yielding April ratoon crops. Dry mass yields of December ratoons were less affected than fresh mass yields and were on average only 38% lower than the April ratoons. Stalks of December ratoons had high fibre content at 12 months of age (Figure 45). Similar differences have been reported from an Australian study (Mc Donald, 2006) in which

cane yields of crops at 52 weeks of age which were started in November and December were approximately 10 000 g m^{-2} (i.e. 37% lower) compared with 16 000 g m^{-2} in crops started in April. It is significant that the author did not report any incidence of lodging and sampling continued unimpeded until crops were 420 days old (Mc Donald, 2006). The yields at 52 weeks of age in the Australian study compare well with the yields at 54 weeks of age presented in Table 19. December ratoons at Triangle in Zimbabwe yielded 30% less fresh cane mass than April ratoons over a period of 8 years (Sweet & Patel, 1985). Rostron (1974a) ascribed poor yields of a December ratoon to lodging. Significantly, Rostron (1974a) also remarked on the slow growth of January and February ratooned crops occurring during August and October when the crops were about 6 months old. Weather and soil data were examined but no reason was proposed for the continued reduced rate of growth of these crops after the winter period (Rostron, 1974a). However, December ratoons, particularly in the case of N26, had relatively high cane yields when going into the colder winter months. Lower temperatures reduced both leaf growth (Inman-Bamber, 1994a) and stalk elongation (Figure 40) and larger portions of photosynthate were stored as sucrose in stalks, particularly in the distal internodes (Figure 48). Growth was expected to have accelerated in response to increasing temperatures and higher daily radiation flux at the start of the second summer, but this was not evident in the December ratoons. Recovery from the restricted growth after winter was slow, even when temperatures and radiation flux favoured good growth rates. It is proposed that a feedback mechanism from the increased levels of sucrose in internodes and particularly in the leaves due to lower temperatures inhibited photosynthesis (Ebrahim, Zingsheim, El-Shourbagy, Moore & Komor, 1998). Translocation of sucrose out of leaves should have increased because of the higher temperatures (Ebrahim *et al*., 1998; Hartt & Burr, 1965) after winter. Higher temperatures also increase leaf production (increasing sink strength) which draws on sucrose, thus weakening the feedback signal (McCormick, Cramer & Watt, 2006) to the photosynthetic processes and eventually photosynthetic rates should be fully restored. The recovery of stalk growth rate is dependent on the establishment of new foliage. The new leaves would restore the photosynthetic function of the plant and together with the newly formed internodes would create additional sinks for sucrose and consequently growth rates would be restored. There was evidence in the final harvests of the December crop that growth rates were increasing. However, the delayed response to good growing conditions of the second summer caused December ratoons to yield substantially less than the March, April, May and August ratoons.

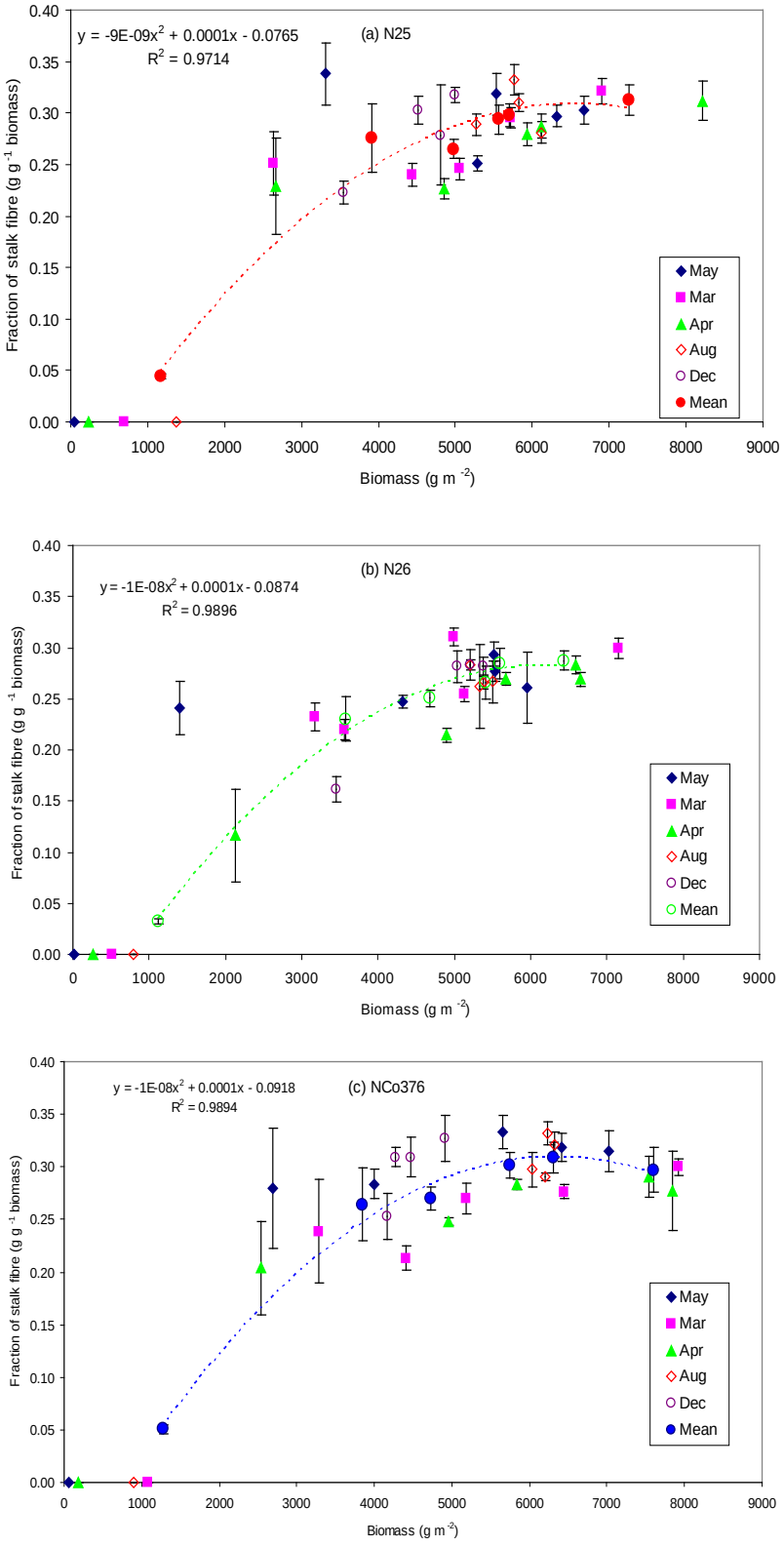


Figure 55 Relationships between fractions of stalk fibre in biomass (g g⁻¹ biomass) and increasing above-ground biomass (g m⁻²) of (a) N25, (b) N26 and (c) NCo376 of March, April, May, August and December ratoons. Trend lines are polynomials fitted to the means and equations are shown on the graphs. Bars denote standard errors (P=0.05).

8.2.2 Partitioning of above-ground biomass to stalk fibre

Trends in biomass partitioning on NCo376, N25 and N26 suggest that about 0.19 to 0.22 of biomass was partitioned to stalk fibre when the accumulated biomass was 3 000 g m^{-2} (Figure 55). The stalk fibre fraction in biomass then rose to slightly above 0.30 as biomass increased to 6 000 g m^{-2} in NCo376 and N25 and was about 0.28 in N26. It is interesting that on average, foliar dry mass represented about 0.30 of biomass in annual NCo376 and N25 crops (Table 10, Figure 37). This indicated that nearly equal portions of biomass was partitioned to stalk fibre and to foliage during the final months of a 12-month old sugarcane crop.

On average, fibre yields of the December ratoons were substantially (11 to 23%) less than of the March, April, May and August ratoons. The low fibre yields of the N26 August and December ratoons were very similar to the average of the December ratoons. Linear regressions of N25 and N26 fibre yields on NCo376 fibre yields during the growth of crops ratooned in March, April, May, August and December suggest that fibre yields of N25 and N26 were 10% and 19% lower than fibre yields of NCo376, respectively (Figure 56). After 12 months of growth, the average N25 and N26 fibre yields (g m^{-2}) were 12.2 (P=0.05) and 18.4% (P=0.05) lower, respectively, than that of NCo376 (Table 21). March and August ratoons yielded

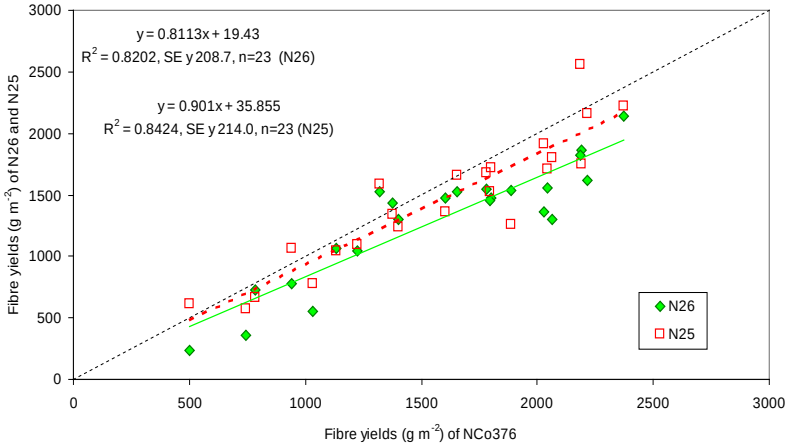


Figure 56 Relationships between fibre yields (g m^{-2}) of N25 (open symbols) and NCo376 and between N26 (closed symbols) and NCo376. Data are from crops started in March, April, May, August and December harvested at 12 months of age. Linear regression equations are shown in the graph for N25 and N26.

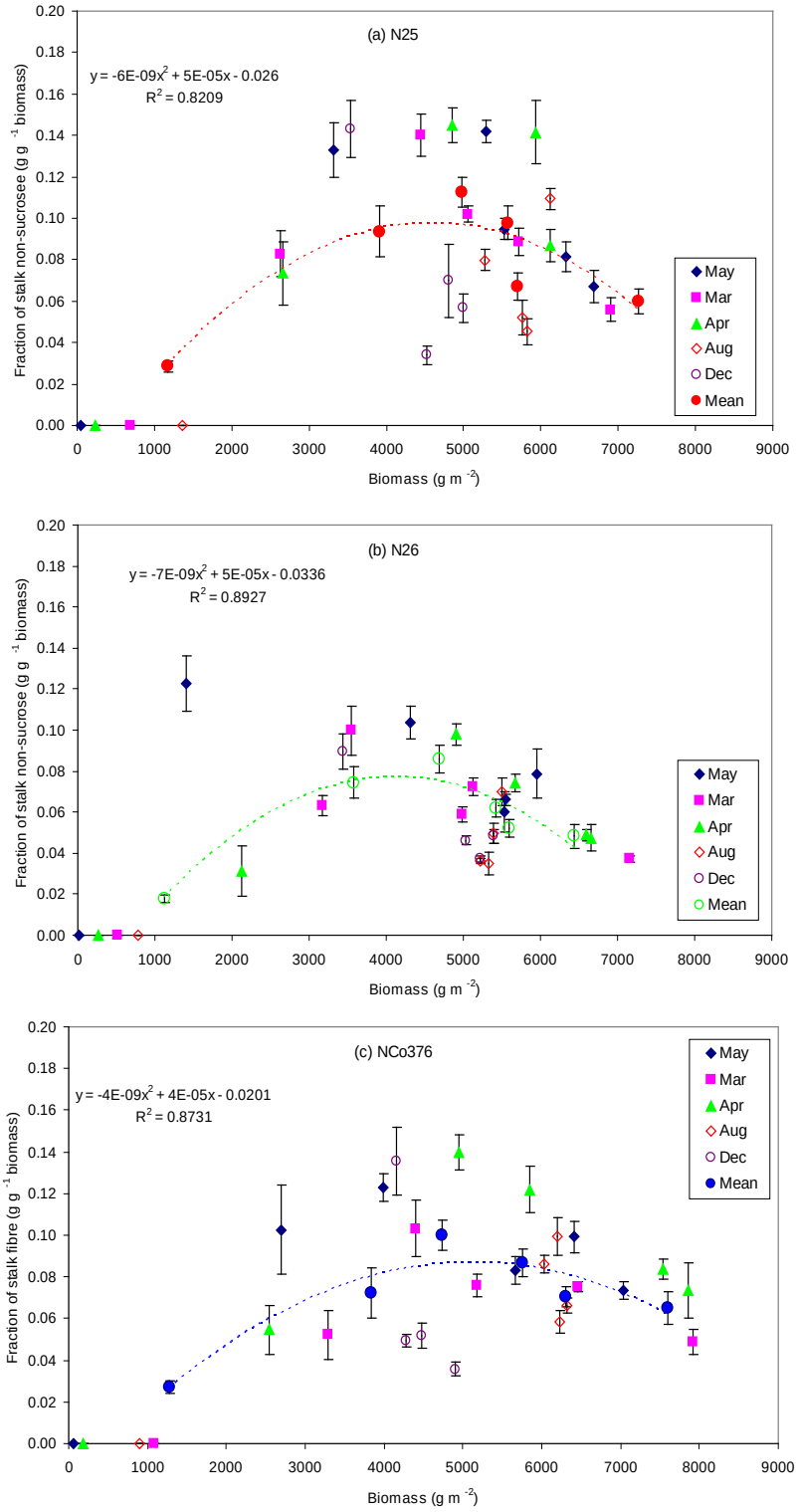


Figure 57 Relationships between fractions of stalk non-sucrose in biomass (g g^{-1} biomass) and increasing above-ground biomass (g m^{-2}) of (a) N25, (b) N26 and (c) NCo376 of March, April, May, August and December ratoon crops. Trend lines are polynomials fitted to the means and equations are shown on the graphs. Bars denote standard errors (P=0.05).

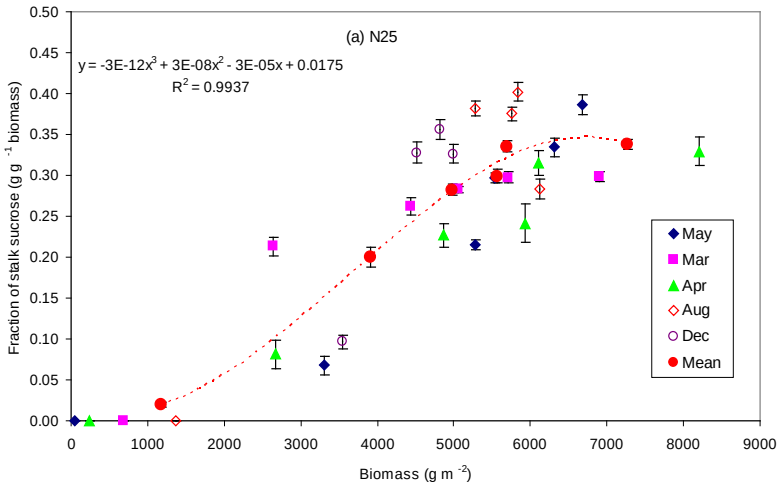
significantly (P=0.05) less fibre than April and May ratoons. December ratoons yielded significantly (P=0.05) less fibre than in the other ratoons. Fibre yields and fibre as a fraction of biomass yield were significantly lower (P=0.05) in N26 and N25 than in NCo376 and significantly lower (P=0.05) in N26 than N25.

8.2.3 Partitioning of above-ground biomass to non-sucrose in stalks

The general trend was an increase in the fraction of stalk non-sucrose in biomass as biomass increased, reaching peaks of 0.14 g g^{-1} in N25 and NCo376 and 0.10 g g^{-1} in N26 when biomass yields were 4 000 to 5 000 g m^{-2} before declining to fractions of about 0.06 g g^{-1} and 0.04 g g^{-1}, respectively, when biomass yields increased further to 7 000 g m^{-2} (Figures 57) in the March, April and May ratoons at 12 to 13 months of age. On average, the non-sucrose mass as fractions of biomass yields were significantly (P=0.05) lower (0.0488 and 0.0359 g g^{-1} biomass , respectively) in August and December ratoons than the mean (0.0779 g g^{-1}) of March, April and May ratoons at the age of 12 months.

8.2.4 Partitioning of above-ground biomass to sucrose

The general trends show that the biomass fraction that was partitioned to sucrose was higher in N26 than in N25 and NCo376 even at low biomass yields (Figure 58). When biomass yields were 6 000 g m^{-2} sucrose fractions in N26 had risen to about 0.35 while in N25 and NCo376 it was between 0.30 and 0.32. The regressions of sucrose yields (g m^{-2}) of N25 and N26 on those of NCo376 indicate d that N25 and N26 yields were not significantly different from NCo376 (Figure 59). This is confirmation of the similar average sucrose yields of NCo376, N25 and N26 at the age of 12 months (Table 21).



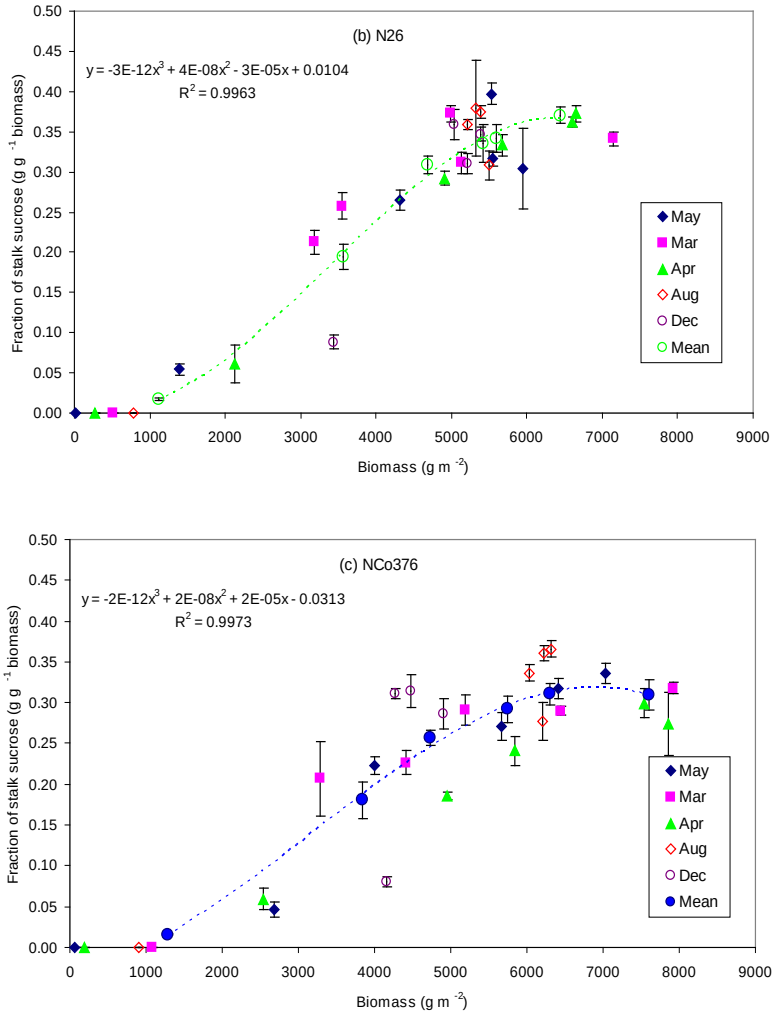


Figure 58 Relationships between fractions of stalk sucrose in biomass (g g^{-1} biomass) and increasing above-ground biomass (g m^{-2}) of (a) N25, (b) N26 and (c) NCo376 of March, April, May, August and December ratoon crops. Trend lines are polynomials fitted to the means and equations are shown on the graphs. Bars denote standard errors (P=0.05).

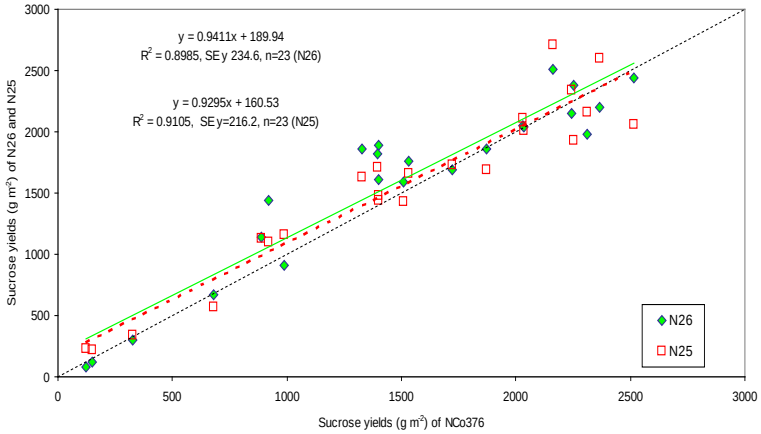


Figure 59 Relationships between sucrose yields (g m⁻²) of N25 (open symbols) and NCo376 and between N26 (closed symbols) and NCo376 of harvestings up to the age of 12 months. Data are from March, April, May, August and December ratoons. Linear regression equations are shown in the graph for N25 and N26.

Table 21 Stalk fibre, stalk sucrose and stalk non-sucrose yields (m⁻²) and their fractions (g g⁻¹) in above-ground biomass of 12-month old NCo376, N25 and N26 of March, April, May, August and December ratoons.

Cultivar/ Crop start date	Stalk fibre g m⁻²	Stalk fibre fraction in biomass	Stalk sucrose g m⁻²	Stalk sucrose fraction in biomass	Stalk non-sucrose g m⁻²	Stalk non-sucrose fraction in biomass
NCo376						
Mar	1 779	0.2761	1 870	0.2902	487	0.0750
Apr	2 192	0.2910	2 254	0.2992	630	0.0837
May	2 042	0.3187	2 030	0.3171	632	0.0992
Aug	2 067	0.3316	2 242	0.3605	360	0.0584
Dec	1 604	0.3272	1 401	0.2859	176	0.0358
N25						
Mar	1 689	0.2951	1 693	0.2974	506	0.0886
Apr	1 759	0.2869	1 935	0.3153	528	0.0868
May	1 877	0.2971	2 107	0.3343	518	0.0813
Aug	1 809	0.3098	2 344	0.4021	260	0.0454
Dec	1 368	0.3028	1 483	0.3279	152	0.0339
N26						
Mar	1 549	0.3109	1 857	0.3727	295	0.0590
Apr	1 861	0.2833	2 385	0.3619	319	0.0488
May	1 544	0.2612	1 799	0.3040	470	0.0787
Aug	1 449	0.2834	1 840	0.3591	185	0.0363
Dec	1 481	0.2836	1 628	0.3100	194	0.0371
Means						
Months						
Mar	1 672bc	0.2940a	1 807c	0.3201d	429b	0.0746b
Apr	1 938a	0.2860a	2 191a	0.3355b	493a	0.0735b
May	1 833a	0.2917a	1 979b	0.3185c	540a	0.0860a
Aug	1 789ab	0.3080a	2 142a	0.3739a	269c	0.0488c
Dec	1 484c	0.3018a	1 504d	0.3079d	174d	0.0359d
SE	72.6	0.0109	80.1	0.0113	27.4	0.0041
LSD(0.05)	155.7	0.0235	171.8	0.0243	58.7	0.0087
Cultivar						
NCo376	1 937a	0.3089c	1 959a	0.3106c	457a	0.0709a
N25	1 700b	0.2982a	1 912a	0.3354b	393b	0.0677a
N26	1 581c	0.2845b	1 902a	0.3415a	293c	0.0519b
SE	54.1	0.0065	56.6	0.0081	13.9	0.0022
LSD(0.05)	116.0	0.0141	121.5	0.0174	29.9	0.0048

Table 22 Stalk fibre, stalk sucrose and stalk non-sucrose yields (g m^{-2}) and their fractions in above-ground biomass at the age of 13 months of NCo376, N25 and N26 crops ratooned in March, April and May.

Cultivar/ ratoon date	Stalk fibre g m^{-2}	Stalk fibre fraction in biomass	Stalk sucrose g m^{-2}	Stalk sucrose fraction in biomass	Stalk non-sucrose g m^{-2}	Stalk non-sucrose fraction in biomass
NCo376						
Mar	2 374	0.2998	2 517	0.3171	387	0.0489
Apr	2 185	0.2774	2 163	0.2745	579	0.0773
May	2 211	0.3145	2 361	0.3375	517	0.0737
N25						
Mar	2 215	0.3217	2 061	0.2974	387	0.0559
Apr	2 565	0.3119	2 711	0.3287	464	0.0564
May	2 028	0.3033	2 580	0.3861	449	0.0672
N26						
Mar	2 143	0.2992	2 437	0.3419	267	0.0373
Apr	1 791	0.2691	2 477	0.3698	316	0.0474
May	1 628	0.2936	2 197	0.3964	331	0.0603
Means						
Months						
Mar	2 244a	0.3069a	2 338a	0.3188b	346.7b	0.0474c
Apr	2 180a	0.2861c	2 450a	0.3144b	452.7a	0.0590b
May	1 956b	0.3028b	2 380a	0.3733a	433.1a	0.0670a
SE	80.6	0.0042	111.5	0.0091	14.88	0.0023
LSD (0.05)	172.8	0.0090	239.1	0.0196	31.92	0.0051
Cultivar						
NCo376	2 257a	0.2972b	2 347a	0.3097b	494.3a	0.0653a
N25	2 269a	0.3123a	2 451a	0.3374b	432.7b	0.0598a
N26	1 854b	0.2873b	2 370a	0.3693a	304.3c	0.0483b
SE	66.2	0.0064	62.5	0.0062	16.89	0.0025
LSD (0.05)	142.1	0.0138	134.1	0.0133	29.8	0.0053

The sucrose yields of the December ratoons were between 17 and 31% (P=0.05) lower than March, April, May and August ratoons at the age of 12 months. The sucrose yields of N26 in the December ratoon were 14% (P=0.05) and 9% higher than of NCo376 and N25, respectively. No differences were found between the sucrose yields of the Queensland cultivars Q96 and Q165 of crops started in December in Ayr, Australia. The December ratoons however, yielded about 33% less sucrose than a June ratoon (McDonald, 2006). Understanding the reasons for poor yields of December ratoon crops is important to mitigate the effects on both the farm and regional mill levels.

8.2.5 Ageing March, April and May ratoon crops

When crops ratooned in March, April and May were harvested at the age of 13 months (Table 22) sucrose yields were increased on average by 25.4, 11.1 and 6.3%, respectively, above that achieved at the age of 12 months (Table 21). The gains in sucrose yields was due mainly to increases in stalk fresh mass in the March and April ratoons and to an increase in sucrose percentage (stalk sucrose content) in the May ratoons. For example, the fresh cane yields of the March ratoons increased from 15 710 $\pm$ 623.8 to 18 939 $\pm$ 850.7 g m^{-2} between the ages of 12 and 13 months, respectively. The sucrose concentration in the May ratoon increased from 0.3185 g sucrose g $biomass^{-1}$ at 12 months to 0.3733 g sucrose g $biomass^{-1}$ at the age of 13 months. The gains during the last month of the growth of were substantial and extending the age of harvesting from 12 to 13 months of these autumn crops is one possible step in developing a strategy of mitigating the poor yields of the December ratoons.

8.3 Concluding Discussion

The growing season had a marked effect on cane fresh mass and sucrose yields as evidenced by December crops having yielded on average 46% less cane fresh mass and 31% less sucrose mass than the April ratoons at the age of 12 months. Generally growth patterns were similar to those seen in individual stalks. The exception was the very high cane yields after 4 months of growth in the December crop of NCo376. The NCo376 December ratoon crops produced a flush of small shoots that were too small to be included in the first harvests but were included in shoot counts that were used to determine shoot densities. Consequently shoot numbers at early harvests were very high and this was reflected in the cane fresh mass yields which were calculated from stalk mass multiplied by shoot numbers. The slower growth rates in the final month of growth of the April and May ratoons are similar to those found in ageing crops in other studies (e.g. Rostron, 1974a; Muchow *et al*., 1994). However, growth rates slowed markedly after about 4 and 8 months in the December and August ratoons, respectively. This was the result of rapidly declining shoot numbers and reduced rates of shoot growth. Cane yields of December ratoons declined after 4 months in NCo376 and after 8 months in N25 and N26 because shoots with harvestable stalks were dying and stalk mass increments were small. The reduced growth rates in the August and December ratoons were associated with declining temperatures (<18°C minimum) and low daily solar radiation (<20MJ m^{-2} d^{-1}) experienced when these crops were about 8 and 4 months old, respectively. In young crops both fibre and non-sucrose concentrations

increased as biomass increased. Fibre levels in stalks were maintained at about 0.30 g g^{-1} biomass in mature crops and were not different at the age of 12 months in different ratoons. Non-sucrose levels however declined by about 50% during the months prior to harvesting to levels between 0.0359 and 0.0860 g g^{-1} biomass when crops were 12 months old. The lower non-sucrose content in the December ratoons at the age of 12 months may be indicative of crop growth rates not having resumed to expected rates after winter. December ratoons of NCo376, N25 and N26 produced cane yields that were not statistically different at the age of 12 months. Their sucrose yields were affected in the same way by the poor growth through winter and early summer. The better sucrose yields attained by the N26 December ratoon crops (compared with NCo376 and N25) before winter were still evident when crops were 12 months old. The poor growth during winter and spring may not be true for all cultivars as evidenced by the relatively better biomass yields of N14 reported by Donaldson *et al.* (2008a). The data presented show that on average NCo376, N25 and N26 produced sucrose yields of 2 389 g m^{-2} at 13 months of age. This was 397 g m^{-2} more than from March, April and May ratoons that were harvested at the age of 12 months. If brix is used for the stock for ethanol production then the potential yields at 12 months were 2 304 g m^{-2} of total sugars. In addition 12-month old ratoon crops (mean of NCo376, N25 and N26) can potentially produce approximately 1 741 g m^{-2} of fibre from stalks which could be used to generate electricity or as stock for ethanol production when the technology becomes commercially viable. The August ratoon of N25 produced significantly (P=0.05) higher sucrose and total sugars (brix) than N26. However, the N25 April ratoon crop yielded significantly less (P=0.05) sucrose and total sugars than N26 and NCo376. On average N26 yielded 7 and 18% less stalk fibre than N25 and NCo376, respectively at the age of 12 months. N26 yielded significantly (P=0.05) more sucrose than NCo376 and N25 in the December ratoons. On average, over the five starting times NCo376, N25 and N26 produced similar sucrose yields (mean 1 924 g m^{-2}) at the age of 12 months.

CHAPTER 9

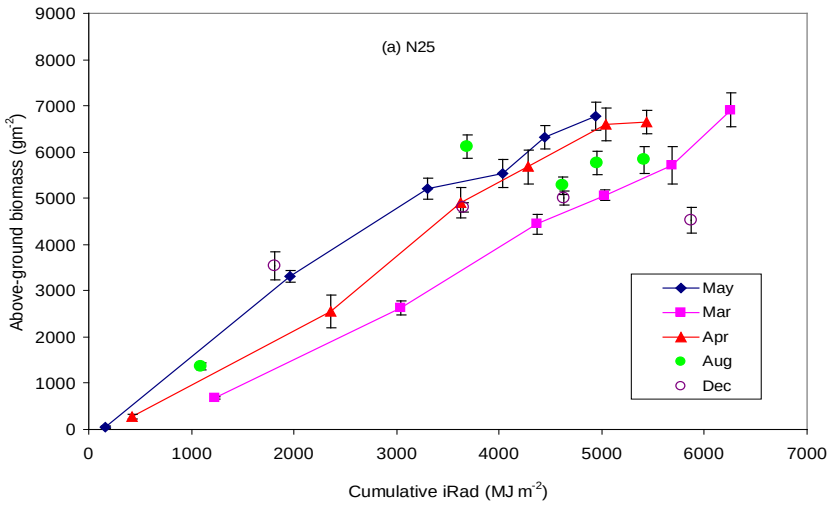
BIOMASS YIELDS AND RADIATION USE EFFICIENCY

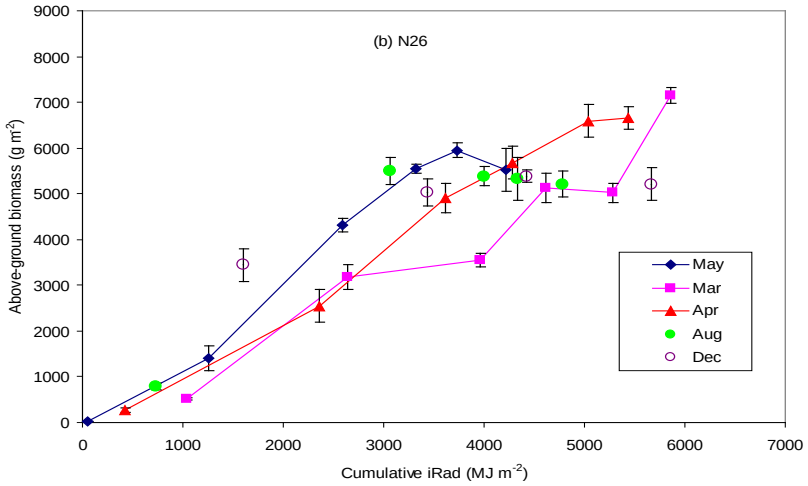
9.1 Introduction

Productivity of sugarcane is most often measured in terms of cane (fresh) yields and sucrose content and these parameters form the basis for cultivar selection. The total above-ground dry matter produced by sugarcane is not routinely measured in field experiments. Few studies have investigated the seasonal effects on biomass production and no more than one or two cultivars have been included in previous studies (e.g. Thompson, 1978; Singels *et al.*, 2005; McDonald, 2006). Therefore there is a need to widen the range of cultivars studied, particularly in relation to season as was done by Gilbert and his co-workers for USA cultivars (Gilbert, Shine, Miller, Rice & Rainbolt, 2005). The review by Thompson (1978) of the season effects on the production of biomass by the South African sugarcane cultivar NCo376 was based on stalk dry mass data reported by Rostron (1974b). Biomass was calculated by assuming that the fraction of trash in biomass was constant at 0.34. The study also expressed productivity in terms of the efficiencies in which incident solar radiant energy was converted into biomass. A better measure of the efficiency of productivity is based on intercepted solar radiation rather than incident solar radiation. The fraction of radiation intercepted by crop canopies is affected by season (Inman-Bamber, 1994b; Singels *et al*., 2005). The efficiency by which intercepted radiant energy is converted into biomass determines the productivity of the crop. Radiation use efficiency (RUE) is defined here as the above-ground biomass (g m^{-2}) produced per unit short wave radiation intercepted (MJ m^{-2}) by the green canopy. Values of RUE between 1.25 g MJ^{-1} (Singels & Smit, 2002) and 1.96 g MJ^{-1} (Muchow *et al*., 1997b) have been quoted for sugarcane in the literature. In this study biomass was calculated as the product of shoot mass and shoot numbers m^{-2}. The fraction of incident solar radiation intercepted by the crop was estimated from measured PAR intercepted at intervals (Chapter 5) during the development of the green canopy and RUE was calculated as the ratio of above-ground biomass to intercepted solar radiation (g shoot dry mass MJ^{-1} intercepted solar radiation).

9.2 Results and Discussion

Some of the data and comments related to radiation interception that were presented in Chapter 5 are repeated here for the sake of continuity.





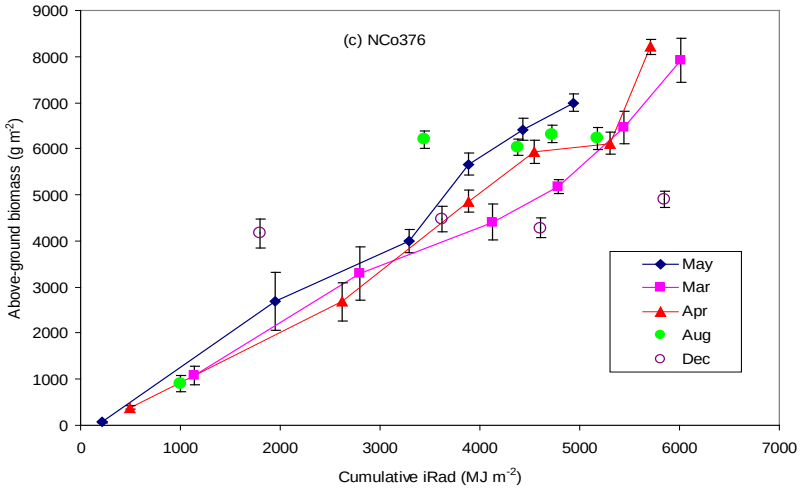


Figure 60 Above-ground biomass yields (g m^{-2}) of (a) N25, (b) N26 and (c) NCo376 crops started in March, April, May, August and December relative to cumulative intercepted solar radiation (MJ m^{-2}). Bars denote standard errors (P=0.05).

9.2.1 Biomass production

March, April and May ratoons tended to accumulate biomass linearly in relation to intercepted radiation, whereas the August and December ratoons accumulated biomass rapidly during early growth (4 and 8 months) and then exhibited little or no gain thereafter (Figure 60). The slowing of biomass accumulation rates in the August and December ratoons was due to lower growth rates of shoots together with declining shoot densities when temperatures and day lengths were declining. Winter conditions (when weekly mean minimum temperatures had dropped to <12°C) were experienced at a younger age (after 5 months) in the December ratoons than in the August ratoons (after 8 months) and consequently biomass yields of December

Table 23 Shoot biomass, aerial biomass yields, fractions of intercepted radiation (iRAD), radiation use efficiencies of 12-month old crops (RUEann), maximum radiation use efficiencies (RUEmax) and age at which highest RUEs (RUEmax) were achieved.

Cultivar /ratoon date	Shoot mass (g)	Biomass (g m^{-2})	fiRad	RUEann (g MJ^{-1})	RUEmax (g MJ^{-1})	Age at RUEmax (days)
N25						
Mar	398.2	5 710	0.87	1.00	1.02	309
Apr	432.8	6 127	0.79	1.15	1.29	329
May	434.2	6 320	0.67	1.42	1.69	245
Aug	479.9	5 829	0.82	1.08	1.66	243
Dec	350.0	4 522	0.89	0.78	2.42	114
NCo376						
Mar	367.4	6 451	0.83	1.19	1.19	364
Apr	406.2	7 536	0.79	1.42	1.42	365
May	385.1	6 413	0.67	1.45	1.46	336
Aug	422.0	6 227	0.78	1.20	1.80	243
Dec	340.0	4 918	0.88	0.84	2.87	114
N26						
Mar	455.7	4 983	0.80	0.95	1.20	245
Apr	560.3	6 515	0.75	1.30	1.36	301
May	554.6	5 952	0.56	1.60	1.67	301
Aug	576.7	5 213	0.72	1.09	1.80	243
Dec	526.3	5 219	0.86	0.84	2.66	114
Means						
Months						
Mar	407.1c	5 715b	0.83	1.05	1.14	306
Apr	466.4ab	6 760a	0.78	1.29	1.36	332
May	457.9ab	6 228a	0.63	1.49	1.61	212
Aug	492.9a	5 756b	0.77	1.12	1.75	243
Dec	405.3c	4 886c	0.87	0.82	2.65	114
SE	9.618	169.4				
LSD (0.05)	20.63	363.4				
Cultivars						
N25	419.0a	5 698b	0.80	1.09	1.62	248
NCo376	384.0b	6 304a	0.79	1.22	1.75	284

N26 SE LSD (0.05)	534.7c 6.90 14.81	5 591b 134.7 264.0	0.74	1.16	1.74	241

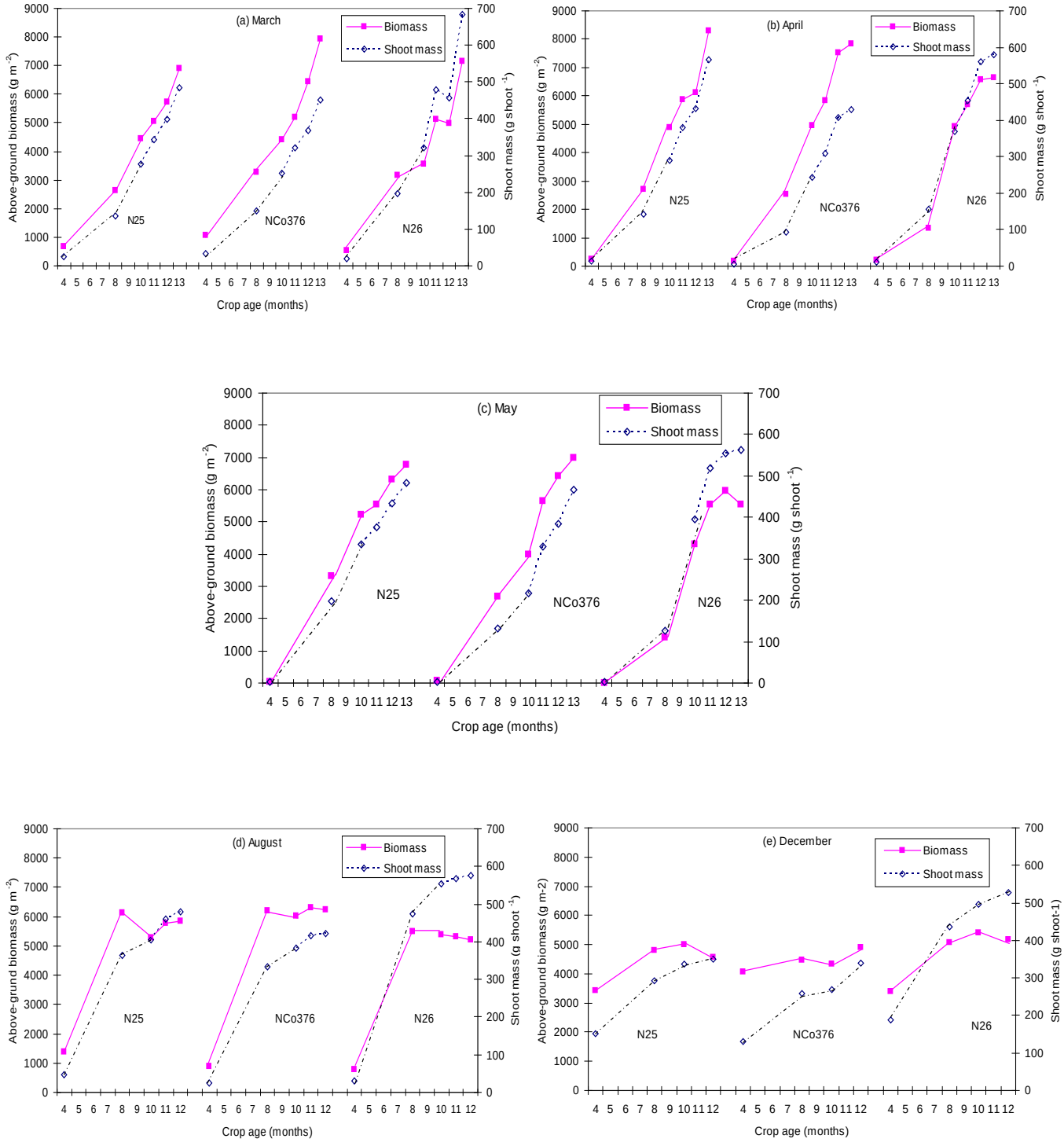


Figure 61 Development of above-ground biomass yields (closed symbols) and shoot mass (open symbols) of N25, NCo376 and N26 in crops started in (a) March (b) April (c) May (d) August and (e) December. (Note: Final harvest points of March, April and May ratoons were at 13 months and August and December ratoons were at 12 months) (Statistical analysis is in Appendix 1(e)).

ratoons were 27.7 and 15.1% (P=0.05) lower than the April and August ratoons, respectively (Table 23). The August ratoons yielded on average 14.9% (P=0.05) less biomass than the April ratoons. March ratoons generally accumulated biomass at lower rates than April and May ratoons and biomass yields were significantly (P=0.05) lower than April and May ratoons (Figure 60, Table 23) at the age of 12 months. The early growth of the N26 May ratoon was retarded by the low winter temperatures so that it yielded significantly less biomass than N25 and NCo376 after 8 months. Biomass yield of the N26 April ratoon was significantly higher (P=0.05) than the March ratoon at the age of 12 months, despite the April ratoon having accumulated only 41% of the March ratoon biomass at the age of 8 months. N26 March, August and December ratoons produced similar biomass yields at the age of 12 months. However, December ratoons of NCo376 and N25 yielded significantly less (23.8 and 20.8% (P= 0.05), respectively) than the March ratoons at the age of 12 months (Table 23).

Above-ground biomass yield was calculated as the product of total dry mass per shoot and shoot density. It was therefore prudent to know how each of these two components affected biomass yields. Shoot densities declined to lower final values in August and December ratoons than in March, April and May ratoons (Figure 41, Appendix 2(d)). Trends in shoot mass development were described by flatter curves as ratoon date progressed from March to December (Figure 61). After gaining mass rapidly during early growth (8 and 4 months), the rate of shoot development slowed during the remaining 4 and 8 months in the August and December ratoons, respectively. The lower accumulation rates in the August and December ratoons coincided with the onset of declining minimum temperatures and declining day lengths. The biomass accumulation rate of N26 appears to have tapered off after about 3000 MJ^{-2} of intercepted solar radiation in the May, August and December ratoons (Figure 60). The lower biomass yields of the March, August and December ratoons of N26 was due to lower shoot densities (August and December ratoons) and to lower shoot mass (March ratoon) at the age of 12 months compared with April and May ratoons. The lower biomass yields of December ratoons of N25 and NCo376 were due to both lower shoot mass and lower shoot densities when compared with other ratoon dates (Figures 41 and 61). The shoot mass of N26 was generally higher than that of N25 and NCo376 in the March, April and May ratoons and was significantly (P=0.05) higher in the August and December ratoons at the age of 12 months. The fitted regression equations describing N25 and N26 biomass

yields in relation to NCo376 biomass yields suggest that N25 produced slightly higher biomass than NCo376 during early growth i.e. before NCo376 had accumulated 3 000 g m^{-2}. Overall, NCo376 produced 10.08 and 11.68% (P=0.05) more above-ground biomass than N25 and N26, respectively (Figure 62).

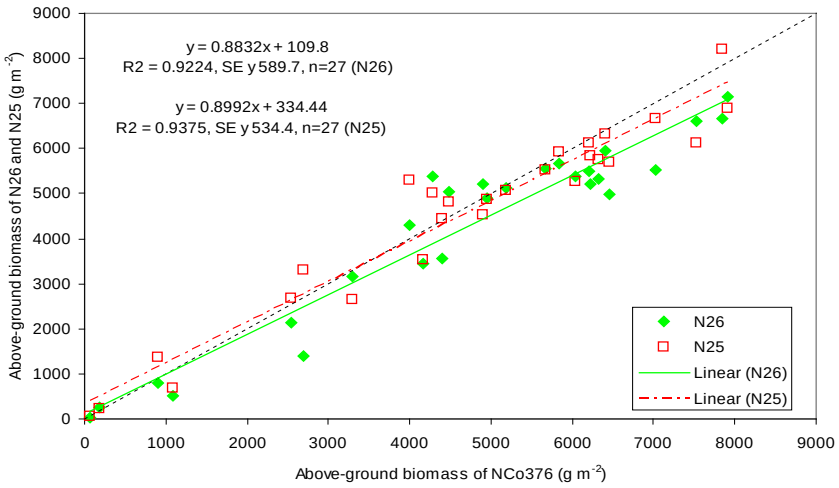


Figure 62 Above-ground biomass yields (g m^{-2}) of N25 (open symbols) and N26 (closed symbols) in relation to biomass yields of NCo376 harvested up to the age of 12 months. Data are from March, April, May, August and December ratoon crops. Linear regression equations of the relationships are shown on the graph.

9.2.2 Radiation use efficiencies (RUE) and fractional radiation interception

Annual incident short wave radiation was similar for the five crop starting times, but slightly lower in the March ratoon crop (Table 24). The difference between the lowest (March ratoon) and the highest (April ratoon) radiation received was 126 MJ m^{-2} which is equivalent to 0.35 MJ m^{-2} d^{-1}. May ratoons intercepted the lowest fractions

Table 24 Incident short wave radiation (m^{-2}) for the duration (days) of measurements of March, April, May, August and December ratoons.

Ratoon date	March	April	May	August	December
Radiation MJ m^{-2}	6 569	6 695	6 623	6 638	6 614
Period (days)	364	365	362	362	357

of incident radiation and December ratoons the highest (Table 23); this was related to the rapid canopy development during the early growth phase (LAI < 2). December ratoons reached full canopy within 77 days while May ratoons took more than 200 days to reach full canopy (Figure 31). The time taken to reach full canopy increased between March and May ratoons and this resulted in the fraction of total radiation intercepted decreasing from March to May ratoons. After winter, canopy development was more rapid and the fraction of radiation intercepted was higher in August and December ratoons (Table 23). The annual fraction of radiation intercepted by N26 in

the May ratoon was low at 0.56, compared with the mean fraction of 0.63 for all three cultivars of the May ratoons. Shoot emergence was slower in N26 (Figure 6) and consequently LAI was lower than in N25 and NCo376 for much of the duration of the crop (Figure 31). The May N25 and NCo376 ratoons were intercepting >75% of incident radiation compared to only 53% intercepted by N26 (Figure 33) at the age of 6 months. Except for slightly higher radiation intercepted in March and August ratoons by N25, radiation interception was very similar in NCo376 and N25. A comparison between the highest instantaneous radiation use efficiencies (RUEmax, i.e. derived by dividing above-ground biomass by intercepted short wave solar radiation to achieve the highest RUE during a period of the crop) and annual radiation use efficiencies (RUEann, derived by dividing above-ground biomass by intercepted short wave solar radiation when crops were 12 months old) could be a useful measure of how RUE changes during crop growth. Differences between RUEmax and RUEann were generally much smaller in March and May ratoons than in August and December ratoons (Table 23). This indicates that some factor was present during phases of growth in the August and December ratoons that reduced RUEs more than in March, April and May ratoons. Both shoot numbers and the mass of individual shoots determine biomass production and therefore factors which affect them will also affect RUE. Shoot senescence in the August and December ratoons started 30 to 50 days before PAR was fully intercepted (Li = >95%) by the canopy. Inman-Bamber (1994b) noted that tiller death started when approximately 70% of PAR was intercepted by the green foliage. Singels & Smit (2002) suggested that shoot phenology is governed by the radiation environment within the row rather than in the inter-row. Light quality was not measured in this study. However, it can be speculated that during canopy closure radiation reaching the lower strata of the canopy was rich in far-red (FR) radiation and depleted in the red (R) and blue wavelengths. This shift in radiation quality, particularly in the R:FR ratio is perceived by chromoprotein pigments (phytochromes and cryptochromes) that initiate mechanisms that modify plant growth (Ballaré *et al*, 1990). This switch in light quality may induce genes to produce growth regulating hormones (auxins) that accelerate stem elongation and reduce tillering (Ballaré *et al*., 2000). It has been proposed that tiller death in winter wheat (*Triticum aestivum*) is initiated by a critical R:FR ratio (Sparkes *et al*., 2006). Rostron (1974a) observed that the cultivar NCo376 which started growing in December had a high number of stalks that elongated rapidly and had smaller basal diameters. April ratoons produced stalks with the largest basal diameters and it was observed that stalk diameters were inversely related to stalk shoot density (Rostron, 1974a). Full canopy cover was reached within 77 days in the

December ratoon but took about 150 days in the April ratoon. In a study by Rostron (1974a) the rate of shoot senescence was very rapid in a December ratoon and shoot density declined more rapidly in crops started after June when temperatures were higher. These are all indications of the plasticity of growth of sugarcane in response to radiation quality and quantity and together with temperature probably mediated gene expression. Low temperatures induce natural ripening in sugarcane stalks (Glasziou, Bull, Hatch & Whiteman, 1965). Photosynthetic efficiency is very sensitive to low temperatures. Lui & Bull (2001) demonstrated from work done by Waldron, Glasziou & Bull, (1967) that when night temperatures changed from 20°C to 10°C, photosynthetic efficiency dropped by 66% in sugarcane. In the present study minimum temperatures dropped below 10°C during 9 weeks after the December ratoon was 4 months old and the crops had accumulated more than 3000 g m^{-2} of above-ground biomass. Low temperatures were therefore the likely reason for curtailed growth of stalks and particularly of leaves, reducing source; also sink storage capacity was reduced by the production of shorter internodes and the concentration of sucrose in the upper part of the stalk was increased. There were indications of a slow recovery in rates of stalk mass accumulation by NCo376 during November. Recovery was however mainly in the form of new foliage production, when minimum daily temperatures had risen above 10°C during the final 4 months. The December ratoons, appeared to be most vulnerable (see yield comparison in Mc Donald, 2006) to the low winter temperatures and displayed slow recovery rates that impacted on subsequent growth. It is therefore postulated that December ratoons were prematurely ripened by low temperatures and that a “feed back” signal from the high sugar levels suppressed photosynthesis in the leaves leading to reduced growth rates (for a review on source-sink regulation see McCormick *et al*., 2006). It is also proposed that the recovery to pre-winter growth rates could only be attained when new leaves and internodes had developed stronger sinks in response to rising temperatures during spring and summer.

9.2.3 Factors affecting radiation use efficiencies

Biomass production has been reported to be strongly correlated with intercepted radiation during the linear phase of growth when crops were healthy and well supplied with nutrients and water (Robertson, Wood & Muchow, 1996). The amount of radiation that was intercepted during 12 months of sugarcane crops was affected by the time taken for the canopy to reach maximum radiation interception. For example, the slow canopy development of crops started in winter led to substantially lower fractions of incident radiation being intercepted than in summer crops when

canopy development was quick (Inman-Bamber, 1994b; Singels *et al*., 2005a). It would therefore be reasonable to expect December ratoons to produce higher biomass yields than June ratoons if RUE is relatively constant (Sinclair & Horie, 1989; Muchow *et al*., 1994). However, it was shown in this study that RUE was not constant and that March, April, May and August ratoons produced better yields than December ratoons (also see Singels *et al.*, 2005a) despite the March, April and May ratoons having intercepted lower fractions of incident radiation. RUEmax values increased between May, August and December ratoons (Table 23). This suggested that early RUE values may have been correlated to temperature. To verify whether temperature had influenced RUE, the data from the present study of the early growth stages (first 4 months) of NCo376, N25 and N26 were analysed by Donaldson, Singels & Smit, (2006). Radiation use efficiencies of crops with LAI >1 were plotted against mean temperatures (daily (maximum + minimum)/2) for the first 4 months of each ratoon crop. They found that RUE increased with increasing mean temperature in the range of 18 to 25°C (Figure 63).

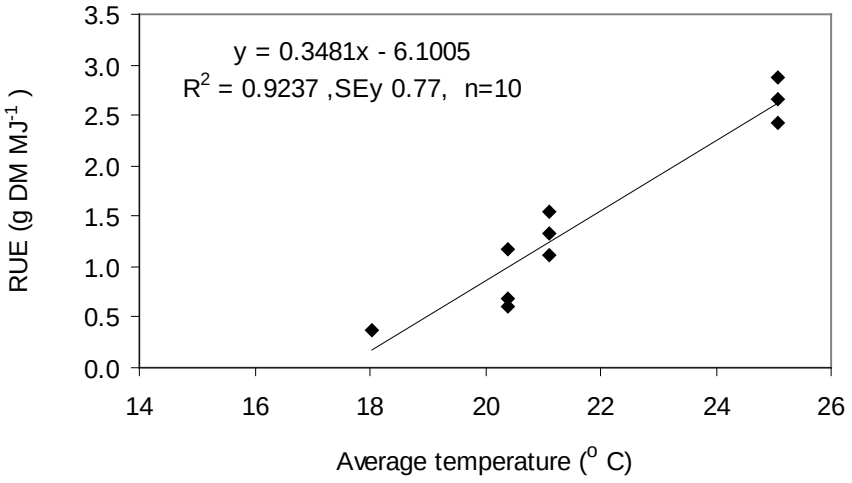


Figure 63 Relationship between radiation use efficiencies (RUE, g DM MJ^{-1} of iRAD) and mean ambient temperatures ((daily max+min)/2) during first 4 months of NCo376, N25 and N26 ratoons at Pongola (after Donaldson *et al.,* 2006).

The merits of having used early growth data to determine RUE were in avoiding possible influences that lodging, flowering and decreasing levels of nitrogen nutrition may have had on photosynthesis and therefore on RUE. Data associated with LAI less than 1.0 were excluded from the analysis because RUEs then decreased (Sinclair & Muchow, 1999). Similar relationships between RUE and temperature have

been reported for maize (Andrade, Uhart & Cirilo, 1993). Martine, Siband & Bonhomme (1999) demonstrated that RUE (intercepted PAR) of sugarcane was 2.38 g MJ^{-1} at 15°C and 3.55 g MJ^{-1} at 26°C. These values of 2.38 g MJ^{-1} and 3.55 g MJ^{-1} which were based on intercepted PAR are higher at 15°C and lower at 26°C than the values from the linear equation y=0.3481x - 6.1005 developed on intercepted solar radiation (Figure 63). RUE based on intercepted solar radiation is typically 50% of the PAR value. Mean daily temperatures fall below 18°C during winter at Pongola and therefore RUEs would be expected to drop to very low levels according to the RUE relationship in Figure 63. Other factors may also influence RUE in crops free of diseases and water stress. For example, RUEs increased with increased row spacing (Singels & Smit, 2002). Crop RUEs also increased as the diffuse:direct ratio of incident radiation increased (Sinclair & Muchow, 1999). Although the effect this has on yields may be relatively small over the entire crop it may nevertheless be substantial over shorter intervals. RUEs were also reported to be different between plant and ratoon crops (Robertson, Wood & Muchow, 1996) and among cultivars (Muchow *et al*., 1997a). A clearer understanding of the interacting G x E factors that influence RUE is needed, particularly when comparisons are made between crops grown in different environments.

9.2.4 Ageing March, April and May ratoon crops

March, April and May ratoons harvested at 12 months of age generally had lower sucrose contents than August and December ratoons. Well fertilised and well irrigated crops that were free of diseases responded well to chemicals that increased stalk sucrose content and consequently increased sucrose yields (Donaldson & Van Staden, 1989; Donaldson, 1994). There are many risks to using such chemicals and alternative techniques of increasing sucrose yields need to be investigated. Biomass yield was on average 1 239 g m^{-2} higher in 13 month old than in 12 month old crops ratooned in March, April and May (Table 25). One possible method of increasing yields of autumn ratoon crops therefore, is to harvest crops at an older age. The average gains from harvesting at the age of 13 months decreased from March to May ratoons. Gains were without loss in RUE in all March ratoons and the N25 April ratoon. In all the other crops gains between the ages of 12 and 13 months were small and were associated with losses in RUE due to loss of shoot numbers and in the case of N26, also due to reduced rates of shoot growth.

Table 25 Shoot mass, above-ground biomass yields, fraction of intercepted solar radiation and radiation use efficiencies (RUE) at 13 months and biomass gains between the ages of 12 and 13 months of March, April and May ratoons.

Cultivar /ratoon date	Shoot mass (g)	Biomass ($g\ m^{-2}$)	fiRad	RUE ($g\ MJ^{-1}$)	Biomass gain between 12 and 13 months ($g\ m^{-2}$)
N25					
Mar	483.8	6 906	0.88	1.01	1 196
Apr	565.8	8 240	0.80	1.44	2 116
May	483.4	6 778	0.69	1.37	358
NCo376					
Mar	450.9	7 917	0.84	1.32	1466
Apr	428.9	7 851	0.80	1.37	315
May	444.7	7 029	0.69	1.42	615
N26					
Mar	684.5	7 150	0.82	1.22	2 167
Apr	578.9	6 627	0.76	1.22	44
May	561.4	5 526	0.59	1.31	-426
Means Month					
Mar	511.7 a	7 324ab	0.85	1.18	1 424
Apr	525.2 a	7 572a	0.79	1.34	825
May	496.5a	6 410b	0.66	1.37	182
SE	20.4	199.3			
LSD (0.05)	43.8	427.5			
Cultivar					
N25	511.7b	6434c	0.79	1.27	1 223
N26	608.2a	7599a	0.72	1.25	799
NCo376	411.5c	7275b	0.78	1.37	695
SE	8.8	112.8			
LSD (0.05)	18.8	242.0			

9.3 Concluding Discussion

There was an early reduction in growth rate of shoots in the December ratoons, and to a lesser extent also in the August ratoons. December ratoons yielded less biomass than March, April, May and August ratoons at the age of 12 months. Reduced growth rates appeared to have been the main reason for lower radiation use efficiencies (RUE). Reduction in RUE in these December ratoon crops coincided with declining temperatures and shorter day lengths experienced after the crops were 4 months old. Average weekly minimum temperatures during this period dropped below 12°C for about 10 weeks. During this period maximum temperatures were about 24°C and average daily incident radiation was about 13 MJm^{-2}. The cultivar N26 accumulated substantially more shoot mass during the first 4 months of growth in the December ratoon than N25 and NCo376 and its yield at the age of 12 months was therefore less affected by the slower growth rates caused by the low temperatures through winter. Death of stalks, as evident in Figure 41 and also reported by Park *et al*.

(2005), may also be the cause of lower rates of biomass accumulation. The highest biomass yields of crops harvested at the age of 12 months were from April and May ratoons despite their low RUEs during early growth. Gains in biomass yields from harvesting crops at 13 months compared with harvesting at the age of 12 months were substantial for all three cultivars of March ratoons and for N25 April ratoons. These differences between cultivars suggest that care may be needed in selecting the appropriate cultivar to be aged with good effect.

CHAPTER 10

FINAL DISCUSSION AND CONCLUSIONS

The growth and yields of the sugarcane cultivars NCo376, N25 and N26 ratooned in March, April, May, August and December were measured using well established methods. The growth of these crops was followed from germination and emergence of the first shoots to final yields after 12 (August and December ratoons) or 13 (March, April and May ratoons) months of growth. Most growth parameters that were analysed could be explained by temperature and radiation, which was experienced during their growth. The March, April and May ratoons experienced declining temperatures and lower daily solar radiation as days shortened during germination and emergence. In later stages of growth temperatures and daily solar radiation were high. The August ratoons emerged when temperatures and daily solar radiation were higher after winter. These crops experienced low temperatures and low daily solar radiation during the final few months as they grew through winter before their final harvest. The December ratoons germinated and emerged when temperatures and daily solar radiation were high. These crops experienced highly suitable growing conditions during their first 4 months before temperatures and solar radiation were low through winter. During the final 3 months of the December ratoon temperatures and solar radiation were high and favorable for high growth rates. It is recommended that in future studies the effects of low temperatures on yields of September, October and November ratoons are quantified to understand its impact on biomass and productivity of other summer harvested crops.

Germination of these ratoon crops was estimated to have taken between 5 (March ratoon) and 15 days (May ratoon) and was strongly correlated to air temperature immediately after the crops were ratooned. The cumulative thermal times needed for germination were estimated to be 94, 98 and 88°C d for NCo376, N25 and N26, respectively. The base temperatures used for calculating thermal times for germination were 12.7, 12.4 and 14.2°C for NCo376, N25 and N26, respectively. N26 would be expected to germinate slower in winter months than NCo376 and N25 because it requires higher temperatures for the germination process than NCo376 and N25.

Shoots continued to emerge as tillering changed from an initial rapid rate to a slower rate before shoots started to senesce. Peak shoot densities were attained at about 500°C d. The rate at which shoots were produced appeared to determine maximum

shoot densities and NCo376 consistently had the highest (62 m^{-2}) and N26 the lowest (28 m^{-2}) SDmax. The wide range of % PAR interception values in the present study and those reported in the literature (Inman-Bamber, 1994b; Zhou *et al*., 2003; Donaldson *et al*., 2003; Keating *et al*., 1999) at the onset of shoot senescence suggest that there is no single fixed quantity of PAR that triggers shoot senescence in sugarcane. However, shoot senescence appeared to start at lower levels of intercepted PAR in low population cultivars (Zhou *et al*., 2003; Donaldson *et al*., 2003). Shoots senesced most rapidly in the August ratoons and final shoot densities were lowest in the August and December ratoons. In the August and December ratoons shoots senesced when temperatures and daily incident solar radiation were high and it was clear that the higher the cumulative thermal time between SDmax and harvest date the lower the final shoot densities of crops. Shoots were produced at a slower rate in March, April and May ratoons and their maximal peak shoot densities (SDmax) were lower than in August and December ratoons. This was so despite shoot population development being expressed in terms of cumulative thermal units and using different base temperatures for cultivars. It therefore appeared inappropriate to described shoot development only in terms of cumulative thermal time (Singels *et al*., 2005b) and sensitivity to changing radiation quality should be considered as a factor governing shoot development. The literature abounds in studies which suggest that shoot development and shoot senescence are modulated by the changes in radiation quality when blue and red wavelengths are absorbed and far-red and green wavelengths are transmitted and reflected by the green components of neighbouring shoots (Casal *et al*., 1985; Skinner & Simmons, 1993; Davis & Simmons, 1994; Sparkes *et al*., 2006). Shoots were initially produced at a faster rate than during a second slower phase before shoot senescence was triggered. The presence of phytochrome and cryptochrome signaling mechanisms and their activation of genes that have profound effects on plant structures have been studied for more than a century (Chen, Chory & Fankhauser, 2004) but to the knowledge of the author these have not been studied in sugarcane. This is probably because sugarcane crops are mostly grown for 12 to 24 months and large differences in early biomass production are often negligible at harvest (Thompson, 1988). Shoot population dynamics were only related to temperature in this study. This is likely to lead to an over simplified understanding of the mechanisms governing shoot production, shoot growth and shoot survival. Efforts to study the influence of radiation quality, specifically R:FR and green radiation on shoot dynamics, as has been done in many of the Poacea crops, are recommended to

uncover the underlying mechanisms that are probably genetically governed in sugarcane.

The rate at which new leaves were produced and older ones died determined the number of green leaves present on a shoot. The collective areas of that number of leaves were the green leaf area per shoot. Smaller leaves were produced during times of low temperatures and shorter day lengths and leaves were larger when temperatures were higher and day lengths longer. Leaf senescence was slowest in the April ratoons and consequently they had the highest peak number of green leaves. However, the area of leaves of the April ratoons tended to be the smallest so that leaf area of shoots was lowest after 4 months and remained relatively low as the crops aged. N26 had the largest leaves and highest shoot leaf area. The leaf area index (LAI) of the crop canopy largely determined how much radiation was intercepted. It was estimated that a LAI of 2 was sufficient to intercept radiation fully. The rate of canopy development determined the fraction of seasonal intercepted radiation. The shoot leaf area was low and tillering slow during early growth of April and May ratoons and therefore LAI remained below 2 for much longer than in March, August and December ratoons. The fraction of intercepted seasonal solar radiation was therefore lowest in the May ratoons (0.63) and highest in the December ratoons (0.88). On average N25 intercepted the highest fraction of seasonal solar radiation and N26 the lowest. The extinction coefficient (k) values estimated in this study were lower than in some previous studies and may be due to the method used; LAI values with their associated PAR interception were selected from each of the ratoons for each cultivar so that LAI ranged from <1 to about 9 when the crops were 4 months old. Contrary to the responses of some C_3 plants to low temperatures (Bonhomme, 2000), the ability of sugarcane to convert intercepted solar radiation into biomass was compromised by low winter temperatures, rather than low radiation flux at Pongola. RUE was strongly correlated to temperature and it could be inferred from this they were lowest during winter when daily minimum temperatures dropped below 10°C. May ratoons produced biomass yields that were only surpassed by the April ratoons. May ratoons had high annual RUEs despite having intercepted a low fraction of seasonal radiation. April ratoons had lower annual RUEs and higher fractions of intercepted seasonal radiation than May ratoons. Despite very high RUEs during the early growth of the December ratoons their annual RUEs were very low and biomass yields were only 78 and 72% of May and April ratoons, respectively. Only above-ground biomass was used in determining RUEs in this study and

subterranean stool growth and roots were not considered. Sugarcane had a root:shoot ratios of 0.4 at 2 months of age after which it declined to about 0.17 at the age of 200 days (Smith, Inman-Bamber & Thorburn, 2005). Clearly, RUEs will be higher if subterranean parts of the sugarcane plant are included in the plant biomass.

Early growth of the December crops was characterised by rapid shoot emergence and the attainment of high maximum shoot densities but relatively low final shoot densities. Leaves were larger and took longer to emerge but reached a maximum size quickly; leaf senescence was faster in December ratoons. Very high LAI were attained and solar radiation was intercepted very efficiently. However, the early vigour of the December ratoons was lost during winter after the age of 4 months. During the final 4 months before the final harvest at the end of November the December ratoons generally gained little additional biomass. Lodging started on the 4 June and this has contributed to loss of potential yield in previous studies but clearly it was not the cause of the poor yield in December ratoons. Cultivars that do not lodge have produced 42% less biomass in a December ratoon compared with a March ratoon. Some cultivars, like N14, have been less affected by low temperatures in the early stages of a December ratoon and growth was not as slow after winter but nevertheless yielded 12% less than high yielding June ratoons. It is clear that after 8 months, shoots that started growing in March, April and May accumulated significantly less stalk fibre, foliage, sucrose and total biomass than shoots that had started growing in August and December. The relative amounts of stalk fibre, foliage, sucrose and biomass were different for ratoon dates. Sucrose mass was affected more by season than the other parameters. For example, lower amounts of sucrose than stalk fibre and foliage were accumulated after 8 months by May, March and April ratoons. August and December ratoons accumulated more sucrose than stalk fibre and foliage mass after 8 months. The fundamental cause of the poor yields of December ratoons appears to be due to their inability to respond to better growing conditions during the second summer. Hypotheses based on this study and previous research could form the framework for elucidating the effects of low temperatures on the growth of sugarcane crops. One such hypothesis is that sucrose translocation slows down markedly during winter. Photosynthesis is also much lower at low temperatures, either as a result of the high sucrose levels operating as a feedback signal (Bull, 1969) or due to the direct effect of low temperatures on the photosynthetic processes or due to both these factors. During low rates of photosynthesis leaf and internode sizes are reduced thus limiting both source and sink capacities. Sucrose continues to accumulate slowly in upper sections of the

stalk, provided the photosynthetic apparatus is not severely impaired by low temperatures and storage capacity is not a limiting factor. Complete reversal of this moribund state of growth depends on the full restoration of the photosynthetic apparatus (increased source) and the presence of larger new internodes (stronger sink).

There was agreement between the findings in this study and that of Rostron (1974a) in the observation that winter and early spring ratooned crops produced the highest yields at the age of 12 months. Rostron (1974a) observed that January and February ratooned crops were most productive when harvested at older ages. It is of particular significance that the growth of the January and February ratoons in the Rostron (1974a) study grew very slowly between August and October. This was also observed in the December ratoon in the present study and gives support to the contention that the growth of the December ratoon was severely retarded by low temperatures and only showed signs of recovery in the last month of growth. This suggests the December ratoons in the present study would have yielded better at ages greater than 12 months, as was the case in the January and February ratoons in the Rostron (1974a) study. It has been demonstrated that in maize some genotypes are able to recover normal growth rates after exposure to low winter temperatures. The recovery after low temperatures is dependent on the integrity of photosynthetic apparatus which contributes to sensitivity of low temperatures (Pietrini, Iannelli, Battiselli, Moscatello, Loreto & Massacci, 1999).

Immediate strategies to overcome these poor yields observed in the December ratoons could include (1) selecting cultivars, like N14, that appear to be less sensitive to the low winter temperatures experienced in the sugar growing regions with a low propensity to flower, and (2) starting the milling/harvesting season earlier to avoid later ratooning summer crops. The strategies could include extending the growth cycle of March, April and May ratoon crops to the age of 13 months. It has been shown that yields are substantially higher when these crops are harvested at 13 months rather than 12 months.

Crops grown under irrigation in the northern regions of the South African sugar industry are generally harvested annually between April and December. The results from this study have shown that March ratoons yield on average 303 g m^{-2} (3.03 t ha^{-1}) more sucrose than December ratoons. The estimated area under irrigation in the northern areas of the South African sugar industry is 55 000 hectares. If the

milling season starts in April and ends in December and assuming that 6 111 hectares are harvested each month then the productivity of this region can be increased by 18 516 tons of sucrose by starting the milling season in March and closing at the end of November. The commercially attainable yields are about 70% of yields achieved in experiments and therefore a more realistic estimate of the benefit to the northern irrigated region is 12 961 tons of sucrose. The remaining areas of the South African sugar industry that are not irrigated (about 256 000 hectares) are prone to varying levels of moisture stress particularly during winter and spring months and it is not known how this will impact on yields and therefore on benefits of shifting the milling period to March-November. Other factors which favour a March ratoon crop are (1) the lower rainfall during March than during December. Harvesting operations are therefore less likely to be disrupted during a March harvest and the possibility of soil compaction will be less. Drier infield conditions during March are likely to mean that less soil will be transported to the mill (2) March crops are not subjected to the deleterious effects of flowering that are often present in December ratoons. (3) December ratoons are also more predisposed to lodging because their stalk bases tend to have smaller diameters. Lodging was first recorded during winter in the December and August ratoons when they were 177 and 268 days old, respectively. In the December ratoons sample harvesting of erect stalks was still possible until the crops were 10 months old, after which no sample harvesting was done until the final harvest at the age of 12 months old. In the August ratoons sample harvesting continued without hindrance until the crops were 12 months old. Sugarcane is known to respond rapidly by establishing an erect top after lodging. However, it is possible that stalks could be smothered and die when the crops have attained a relatively high biomass when they lodge. The possible negative impacts of lodging on final shoot numbers and consequently on biomass can not be ignored (Muchow, Wood & Robertson, 1995; Rostron, 1974a; Singh, Chapman, Jackson & Lawson, 2002). Stalk death would be reflected in marked decreases in shoot densities and increases in the trash component. December ratoons in the present study had the highest fraction of trash in biomass but this was explained by the higher thermal time between SDmax and harvest date. There were also no sharp declines in shoot densities after lodging. Lodging therefore did not accelerate shoot senescence in the present study.

This study has also quantified the amounts of trash, stalk fibre and sugars that current commercial cultivars can produce under non-limiting water and nutrient conditions. The average above-ground biomass yield of NCo376, N25 and N26 was

5 864 g m^{-2} at the age of 12 months. On average 30% of above-ground biomass was allocated to foliage (fibre), 30% to stalk fibre, 34% to sucrose and 6% to non-sucrose. It is proposed that the green leaf portion of the crop foliage (about 835 g m^{-2}) should be left in the field to ameliorate or maintain soil health and recycle nutrients. The remaining "dead trash" portion could be used together with the stalk fibre for generating electricity or in the production of bio-ethanol from lignocellulose fibres. The potential combined dead trash and stalk fibre yields amount to an average of 2 680 g m^{-2} (26.80 t ha^{-1}); 66% in the form of stalk fibre and 34% in leaf fibre. If the crop is grown as a stock for ethanol production then the highest potential yield of total fermentable stalk sugars from the three cultivars would be 2 416 g m^{-2} (24.16 tons ha^{-1}) of which the average potential sucrose yield in these crops was 1 924 g m^{-2} (19.24 tons ha^{-1}).

NCo376 produced the highest biomass yields in four of the five ratoon dates and therefore the highest average biomass yields (6 304 g m^{-2}). The one exception was the higher biomass yields produced by N26 in the December ratoon. However, the difference between the highest and lowest biomass yields of the cultivars NCo376, N25 and N26 was 713 g m^{-2} (7.13 tons ha^{-1}). The partitioning of biomass to sucrose was highest in N26 (0.34), however sucrose yields of the three cultivars were very similar and ranged from 1 959 g m^{-2} (19.59 tons ha^{-1}) for NCo376 to 1 902 g m^{-2} (19.02 tons ha^{-1}) for N26.

Data described in this thesis in conjunction with data from two experiments conducted at La Mercy (Inman-Bamber, 1994b; McGlinchey & Inman-Bamber, 1996) have been used to develop a simple model of canopy development, Canesim (Singels & Donaldson, 2000). The Canesim model is widely used in research by scientists at the South African Sugarcane Institute (SASRI) and has been used to provide advice on irrigation scheduling to farmers.

Genetic coefficients (Boote *et al*., 2003) are cultivar specific characteristics that are represented by numeric values that are used in modeling. Data from this study together with results from a similar experiment conducted at Mount Edgecombe by K.A. Redshaw (described by Singels *et al*., 2005b) were analysed to identify various canopy parameters that are stable across seasons, locality and time of year. Among the parameters tested, maximum leaf size was found to be the only stable cultivar specific parameter that could be used to model cultivar-specific canopy development.

The low yields of the December ratoons were associated with poor response of the crops to higher temperatures in the second summer when the crops were 8 to 12 months old. The high sucrose content of stalks at the end of winter probably lead to feedback signaling of sugars from the stalk (sink) to the leaves (source) which down regulated photosynthesis. This suppressed the crops ability to respond to higher temperatures through spring and into summer. It is unlikely that these events are peculiar to December ratooned crops and they should apply to all summer harvested crops. Their effects on various parameters of yields are expected to depend on (1) the duration and severity of the cold winter months, (2) the age at which the crop experiences winter, (3) the time and duration of good growing conditions after winter and (4) the genetic variation in tolerating low temperatures and/or the ability to recover from the low temperatures. For example, based on the present knowledge of NCo376, it is postulated that there will be a linear decline in sucrose content (fresh mass) of crops ratooned between September and April. This is because each ratoon will experience winter at a different age and each ratoon will have stalks (culm) that will respond differently to winter temperatures and consequently to spring and summer temperatures related to their age and size. Furthermore, crops ratooned from May to July emerge during winter and their canopy development is slow and stalk elongation is delayed until after winter. After stalk emergence the growth of May, June and July ratoons can be expected to be linear for much of the crop period, until they experience winter. Our knowledge of sugarcane physiology can be expanded by studying, in more detail, how crops of different ages, particularly summer ratoons, respond to low temperatures and how the responses determine the yields of 12-month old crops. In this study, data were presented which links the recently identified feedback signaling of sugars (McCormick *et al*., 2006) that reduces photosynthesis to the poor yields in December ratooned sugarcane crops. This phenomenon of poor spring growth during the December ratoon has recently been reviewed and named the reduced spring growth phenomenon (RSGP) by Van Heerden, Donaldson, Watt & Singels (2010). A project at SASRI will incorporate the feedback mechanisms into the CANEGRO model to study its effects on yields of crops ratooned throughout the milling seasons. Data from this thesis can be used to calibrate or validate the model. This will enhance the capability of the CANEGRO model to predict seasonal effects on yields of sugarcane crops and it will lead to further insights into the physiology of sugarcane.

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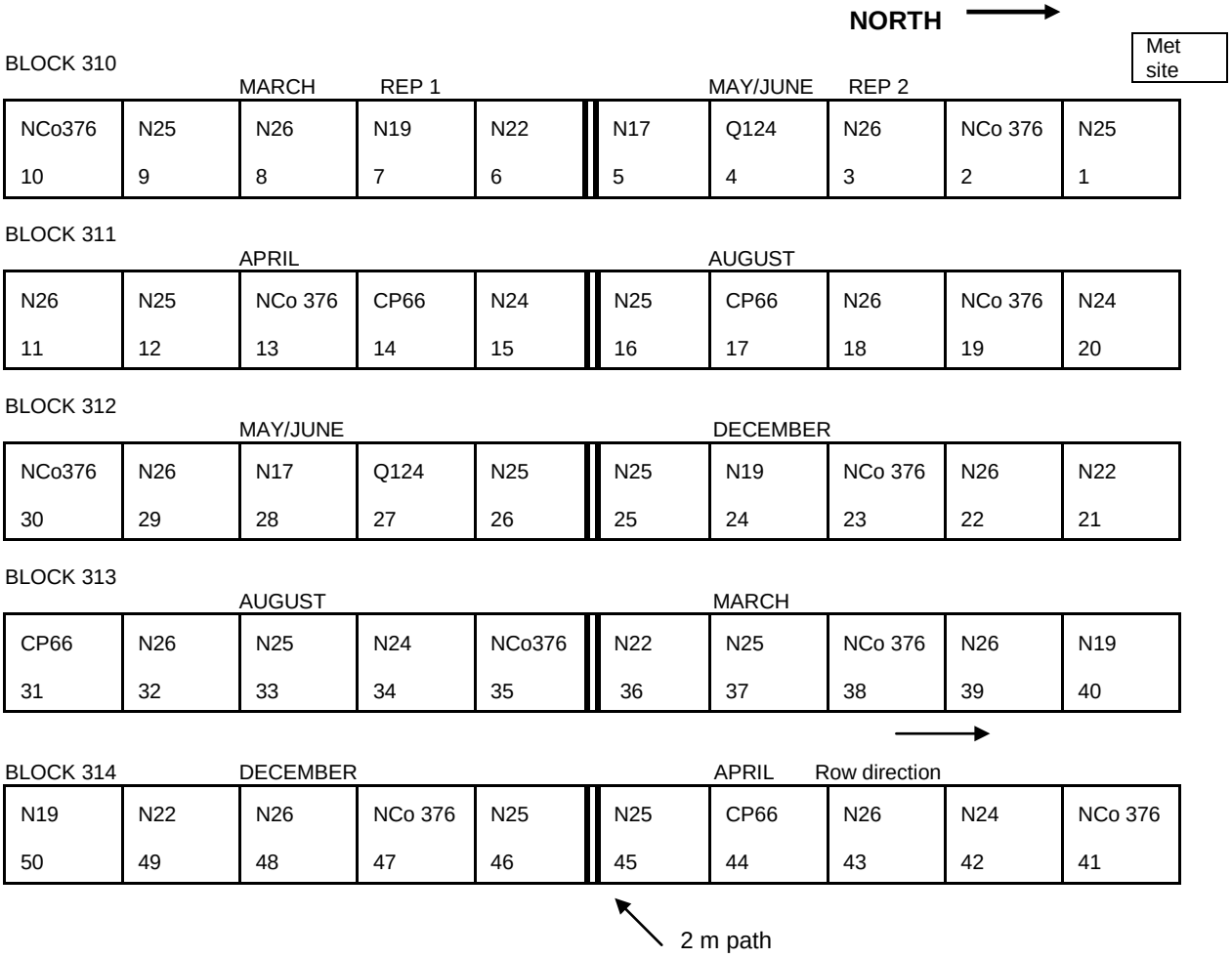
LIST TO APPENDIXES

Appendix 1(a) Field layout of the sugarcane trial at Pongola Experiment Station (Not to scale)



NOTE: All NCo376, N25 and N26 plots were 23m long. Plots of all other cultivars were 18m long.

Appendix 1(b) Polynomial functions derived from regressing intercepted PAR (iPAR=y) with time as days (=x) after ratoon dates for the R2 crops.

March ratoon Cultivars	Polynomial functions	R^2
NCo376	$y = 0.0000253x^3 - 0.0119353x^2 + 1.8318377x - 5.9243426$	0.9612
N25	$y = 0.000026x^3 - 0.012736x^2 + 2.007839x - 8.436621$	0.9726
N26	$y = 0.0000205x^3 - 0.0101014x^2 + 1.6499343x - 6.8296585$	0.9680

April ratoon Cultivars	Polynomial functions	R^2
NCo376	$y = -0.000014x^3 + 0.003864x^2 + 0.304960x - 0.568692$	0.9776
N25	$y = -0.0000143x^3 + 0.0040032x^2 + 0.3121442x - 2.1805523$	0.9851
N26	$y = 0.000015x^3 - 0.003869x^2 + 0.749135x - 8.734896$	0.9942
May ratoon Cultivars	Polynomial functions	R^2
NCo376	$y = -0.000017x^3 + 0.007125x^2 - 0.332773x + 2.360166$	0.9971
N25	$y = -0.000024x^3 + 0.010313x^2 - 0.692087x + 7.751589$	0.9656
N26	$y = -0.000006x^3 + 0.004391x^2 - 0.366308x + 4.573959$	0.9731

August ratoon Cultivars	Polynomial functions	R^2
NCo376	$y = 0.000024x^3 - 0.013131x^2 + 2.449328x - 62.635648$	0.9963
N25	$y = 0.000024x^3 - 0.013658x^2 + 2.604727x - 66.620214$	0.9967
N26	$y = -0.000003x^3 - 0.001523x^2 + 1.045066x - 30.180922$	0.9986
December ratoon Cultivars	Polynomial functions	R^2
NCo376	$y = 0.000083x^3 - 0.027522x^2 + 3.055603x - 16.975926$	0.9965
N25	$y = 0.000074x^3 - 0.025955x^2 + 3.012950x - 17.345093$	0.9992
N26	$y = 0.000023x^3 - 0.012425x^2 + 2.084733x - 12.109516$	0.9982

Appendix 1(c) Dates on which lodging was first recorded in plots of R2 and the R3 crops. [No dates indicate no lodging].

Ratoon & cycle	Cultivar	R2 Rep 1	R2 Rep 2	R3
March	NCo376	17/2/99		8/11/00
	N25	6/1/99	6/1/99	8/11/00
	N26	21/12/98	21/12/98	8/11/00
April	NCo376			None
	N25		17/2/99	
	N26	6/1/99		
May R2 June R3	NCo376	15/5/99	15/5/99	7/3/00
	N25	15/5/99	15/5/99	7/3/00
	N26	15/5/99	15/5/99	7/3/00
August	NCo376	29/4/99		27/3/00
	N25	15/5/99		27/3/00
	N26	29/4/99		27/3/00
December	NCo376	4/6/99	4/6/99	21/6/00
	N25	4/6/99	4/6/99	21/6/00
	N26	4/6/99	4/6/99	21/6/00

Appendix 1(d) Dates and age of destructive sampling.

1st CYCLE (R2)	March crop					
Sampling date	8/07/98	3/11/98	6/01/99	2/02/99	2/03/99	30/03/99
Age-days	127	245	309	336	364	392
	April crop					
Sampling date	6/07/98	9/12/98	3/02/99	3/03/99	8/04/99	3/05/99
Age-days	120	245	301	329	365	390
	May crop					
Sampling date	8/09/98	6/01/99	3/03/99	7/04/99	3/05/99	7/07/99
Age-days	125	245	301	336	362	397
	August crop					
Sampling date	10/12/99	6/04/99	7/07/99	1/07/99	3/08/99	
Age-days	126	243	305	329	362	
	December crop					
Sampling date	1/04/99	3/08/00	30/09/00		30/11/00	
Age-days	114	238	296		357	
2nd CYCLE (R3)	March crop					
Sampling date	3/07/00	1/11/00			6/03/01	
Age-days	117	238			363	
	April crop					
Sampling date	1/08/00	12/12/00			1/04/01	
Age-days	117	250			360	
	June crop					
Sampling date	1/09/00	1/02/00			1/07/00	
Age-days	83	236			357	
	August crop					
Sampling date	1/12/99	5/04/00			1/08/00	
Age-days	117	243			361	
	December crop					
Sampling date	5/04/00	1/08/00			11/12/00	
Age-days	119	237			369	

Appendix 1(e) Summary of statistical analysis of selected yield components in R2 crops.

Variance components	Biomass g m^{-2}	Stalk DM g m^{-2}	Green foliage g m^{-2}	Dead trash g m^{-2}	Stalk FM g m^{-2}	Sucrose g m^{-2}	Stalk density m^{-2}
Residual							
Estimate	5252	3072	681.7	188.4	3072	991.6	1911.7
SE	3130	183	40.60	11.2	183	59	1139.4
Chi square probability							
Cultivar	0.003	0.006	50.8	<0.001	0.006	0.284	<0.001
MonthXcultivar	0.450	0.584	28.7	0.763	0.584	0.006	0.754
AgeXcultivar	0.003	0.002	52.6	<0.001	0.002	0.173	<0.001
Main effects							
Cultivars							
SED	134.7	103	45.6	26.9	103.2	41.09	0.5433
LSD (0.05)	264.0	202	89.3	52.8	202.2	80.54	1.07
LSD (0.01)	346.7	266	117.4	69.4	265.8	105.85	1.40
Interactions							
SED							
MonthXcultivar	649	483	245	104	483	232.3	1.99
Cultivar	708	525	268	111	525	255.8	2.12
Month	300	230	102	60	230	91.12	1.21

Appendix 1(f) Summary of statistical analysis of selected components of shoot yields in R2 crops.

Variance components	Stalk DM g $stalk^{-1}$	Brix g $stalk^{-1}$	Fibre g $stalk^{-1}$	Sucrose g $stalk^{-1}$	Non-sucrose g $stalk^{-1}$
Residual					
Estimate	1480	737.2	245.2	620.7	41.87
SE	84	43.8	31.8	36.9	2.44
Chi square probability					
Cultivar	<0.001	<0.001	<0.001	<0.001	<0.001
MonthXcultivar	0.634	0.927	0.162	0.389	0.004
AgeXcultivar	<0.001	<0.001	<0.001	<0.001	<0.001
Main effects					
Cultivars					
SED	5.85	10.13	2.69	4.07	0.911
LSD (0.05)	11.46	19.85	5.27	7.97	1.784
LSD (0.01)	15.06	26.10	6.92	10.47	2.346
Interactions					
SED					
MonthXcultivar	28.55	19.86	12.41	17.36	5.67
Cultivar	31.14	21.48	13.49	18.74	6.27
Month	13.00	10.13	5.94	9.05	2.02

Appendix 1(g) Statistical analysis of components at the age of 12 months with particular reference to Chapter 6.

Variance components	Biomass g m^{-2}	Green foliage g m^{-2}	Dead trash g m^{-2}	Potential trash g m^{-2}	Fraction of potential trash in biomass g g^{-1}
Residual Estimate	628483	56080	24640	89570	0.0012
Chi square probability					
Cultivar	<0.001	0.17	<0.001	<0.001	0.549
MonthXcultivar	<0.001	<0.001	<0.001	<0.001	<0.001
AgeXcultivar	0.024	<0.001	0.005	<0.001	0.001
Main effects Cultivars					
SED	177.3	53	35	67	0.01
LSD (0.05)	347.5	104	69	131	0.02
Interactions SED					
MonthXcultivar	396.4	118.4	78.49	149.6	0.017
Cultivar	396.4	118.4	78.49	149.6	0.017
Month	396.4	118.4	78.49	149.6	0.017

Appendix 2(a) Maximum shoot density (SDmax) m^{-2} of NCo376, N25 and N26 from crops of five starting months of the R2 and R3 crops.

	March	April	May/June	August	December
NCo376 R2	39.8	42.9	38.3	42.7	62.7
R3	59.3	49.8	42.3	45.6	62.9
N25 R2	36.5	32.1	32.4	33.1	52.8
R3	38.2	36.8	35.9	39.4	38.9
N26 R2	30.4	26.4	16.1	27.0	30.8
R3	42.1	34.1	25.9	31.3	43.9

Ranked Cultivar Means (REML adjusted)	R2	R3
	NCo376 45.3	NCo376 39.6
	N25 37.4	N25 32.8
	N26 26.7	N26 28.8
Ranked starting date Means (REML adjusted)	December 45.1	June 49.3
	March 32.8	December 45.7
	April 30.9	August 39.7
	August 30.5	March 29.7
	May 25.1	April 13.6
LSD (0.01)	13.4	10.9

Appendix 2(b) Cumulative thermal time (base 16 ºC) and days (in parenthesis) taken to reach maximum shoot density (SD max) of NCo376, N25 and N26 from five starting months of the R2 and R3 crops.

	March	April	May/June	August	December
NCo376 R2	531(76)	440 (154)	461 (169)	390 (90)	655 (72)
R3	485(159)	587 (208)	664 (175)	573 (117)	399 (49)
N25 R2	478 (58)	440 (154)	461 (169)	496 (104)	655 (72)
R3	485 (159)	587 (208)	664 (175)	573 (117)	644 (76)
N26 R2	478 (58)	440 (154)	461 (169)	496 (104)	655 (72)
R3	485 (159)	643 (216)	664 (175)	573 (117)	644 (76)
Means R2	499 (64)	440 (154)	477 (172)	476 (101)	655 (70)
R3	485 (159)	599 (210)	660 (174)	573 (117)	595 (71)
Grand mean	492 (109)	520 (182)	569 (173)	525 (109)	625 (70)

Appendix 2(c) Percentage radiation intercepted at SDmax of NCo376, N25 and N26 in R2 crops started in March, April, May, August and December.

	March	April	May	August	December
NCo376	78	100	67	68	91
N25	71	88	75	83	93
N26	55	71	41	42	82
Mean	68	86	61	64	89

Appendix 2(d) Final shoot density (SDfin) m^{-2} of NCo376, N25 and N26 from five starting months of the R2 crops.

	March	April	May	August	December
NCo376	17.6	18.6	16.7	14.7	14.4
N25	14.3	14.1	14.5	12.1	12.9
N26	10.9	11.8	10.7	9.1	9.9

Ranked: Cultivar	NCo376	N25	N26	SED
Means	16.4	13.6	10.5	2.1

Ranked: Starting month	April	May	March	Dec	Aug	SED
Means	14.8	14.3	14.2	12.4	11.9	1.2

Appendix 3 Linear functions derived from regressing number of senesced leaves on total number of leaves per stalk and on cumulative thermal units (°C d).

Crops	Total number of leaves	R^2	Cumulative thermal units	R^2
NCo376				
March	y=0.606x-3.017	0.957	y=0.0051x-1.639	0.955
April	y=0.579x-5.066	0.909	y=0.0039x-2.519	0.954
May	y=0.809x-8.261	0.922	y=0.0046x-3.715	0.955
August	y=1.044x-11.293	0.979	y=0.0061x-4.969	0.974
December	y=1.010x-10.519	0.976	y=0.0068x-5.781	0.961
N25				
March	y=0.681x-4.149	0.963	y=0.0055x-1.869	0.967
April	y=0.536x-4.119	0.914	y=0.0037x-1.917	0.953
May	y=0.673x-6.739	0.927	y=0.0042x-2.625	0.958
August	y=1.045x-11.55	0.981	y=0.0063x-4.969	0.974
December	y=1.035x-10.21	0.976	y=0.0066x-5.098	0.954
N26				
March	y=0.591x-2.380	0.963	y=0.0065x-5.185	0.951
April	y=0.545x-4.159	0.946	y=0.0036x-1.542	0.961
May	y=0.667x-5.995	0.903	y=0.0041x-3.353	0.951
August	y=1.032x-11.422	0.975	y=0.006x-5.091	0.973
December	y=0.906x-9.082	0.950	y=0.0051x-1.303	0.973

Appendix 4 Number of shoots with various numbers of leaves and presence or absence of a stalk apex.

No. of leaves shoot^{-1}		4	5	6	7	8	9	10	11	12	13	14	15	16
NCo376	Crop													
No.	Mar	0	0	0	1	3	6	1	3	0	1	4	0	3
shoots	Apr	0	0	0	0	2	6	5	7	0	0	0	0	0
measured	Aug	0	0	3	3	5	5	5	0	1	1	1	0	0
NCo376														
No.	Mar				0	0	1	1	3		1	3		3
shoots	Apr					0	2	3	3					
with stalk	Aug			0	0	0	5	5		1	1	1		
apex														
N25														
No.	Mar	0	0	0	1	1	0	0	2	3	0	2	0	0
shoots	Apr	0	0	0	0	0	8	9	4	0	0	0	0	0
measured	Aug	0	0	3	1	1	2	3	5	4	1	1	1	0
N25														
No.	Mar				0	0			0	1		2		
shoots	Apr						2	4	3					
with stalk	Aug			0	0	0	0	2	5	3	1	1	1	
apex														
N26														
No.	Mar	1	1	0	1	1	4	3	1	4	3	2	0	0
shoots	Apr	0	0	0	0	1	9	10	4	0	0	0	0	0
measured	Aug	0	0	1		3	3	5	5	4	2	0	0	0
N26														
No.	Mar	0	0		0	0	0	0	1	0	3	2		
shoots	Apr					0	4	4	1					
with stalk	Aug			0	0	0	0	4	4	3	2			
apex														

Appendix 5 Derivation of base temperature for emergence of NCo376 from mean temperature during emergence (T) and days taken to emergence of the first shoot (d). LstStdev is the derived base temperature (12.10°C).

Ratoon month	T	d	d^2	T^2	Td^2	Td	T^2d^2	dT^2	Lst Stdev
Apr	21.7	10.76	115.78	470.9	2512.4	233.5	54518.5	5066.8	
May	20.6	12.26	150.31	424.4	3096.3	252.6	63784.5	5202.7	
June	17.8	17.59	309.41	316.8	5507.5	313.1	98032.9	5573.2	
Aug	18.8	13.81	190.72	353.4	3585.5	259.6	67406.7	4881.0	
Dec	24.0	7.84	61.46	576.0	1475.2	188.2	35404.2	4515.8	
Sum	102.9	62.3	827.7	2141.5	16176.8	1246.9	319146.8	25239.5	12.10

Appendix 6 Monthly mean day lengths (hours) at Pongola

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
13.51	12.91	12.14	11.33	10.65	10.31	10.47	11.06	11.87	12.68	13.37	13.69

LIST OF PUBLICATIONS AND PRESENTATIONS

The following is a list publications and presentations at conferences of data produced in this project and are directly or indirectly associated with the thesis.

SINGELS, A. & DONALDSON, R.A. 2000. A simple model of unstressed sugarcane canopy development. *Proc. S Afr. Sug. Technol. Ass.* 74, 151-154.

O'LEARY, G.J. & DONALDSON, R.A. 2000. Validation of a non-destructive leaf area index measuring device in sugarcane. *Proc. S Afr. Sug. Technol. Ass.* 74, 167-168.

DONALDSON, R.A., REDSHAW, K.A. & SINGELS, A. 2003. In search of parameters to model cultivar-specific canopy development. *Proc. S Afr. Sug. Technol. Ass.* 77, 605-609.

SINGELS, A., DONALDSON, R.A. & SMIT, M.A. 2005. Improving biomass production and partitioning in sugarcane: Theory and Practice. *Field Crops Res.* 92, 291-303.

DONALDSON, R.A., SINGELS, A. & SMIT, M.A. 2006. Effect of crop start date on radiation use efficiency in ratoon crops of three sugarcane cultivars. *Comb. Congr. Soil Sci. Soc. SA and SA Soc. Crop Prod.* 23-26 January 2006, Durban, SA.

DONALDSON, R.A., REDSHAW, K.A., RHODES, R. & VAN ANTWERPEN, R. 2008a. Season effects on productivity of some commercial South African cultivars. I: Biomass and radiation use efficiencies. *Proc. S Afr. Sug. Technol. Ass.* 81, 517-527.

DONALDSON, R.A., REDSHAW, K.A., RHODES, R. & VAN ANTWERPEN, R. 2008b. Season effects on productivity of some commercial South African cultivars, II: Trash production. *Proc. S Afr. Sug. Technol. Ass.* 81, 528-538.

VAN HEERDEN, P.D.R., DONALDSON, R.A., WATT, D.A. & SINGELS, A. 2010. Biomass accumulation in sugarcane – unraveling the factors underpinning reduced growth phenomena. *Journal of Experimental Botany* (submitted February 2010).