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Constraints to High Yield and CCS in Large and Lodged Cane Crops

Thesis submitted by

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(Gurmit Singh) (Date)

Abstract

Previous research in northern Australia and in Hawaii has suggested that large lodged crops of sugarcane experience a marked slow-down in yield accumulation prior to the normal commercial harvest. Cane yield may be as much as 40% below that expected if growth continued at rates occurring prior to the slowdown. Various explanations for this slowdown include lodging induced-stalk death and loss, reduced radiation interception as a result of lodging, seasonal factors and increased crop age.

The primary objective of this thesis was to identify constraint(s) to the production of biomass and sugar in large and lodged sugarcane crops and then interpret and explain the effects of the identified factor(s) on growth processes such as stalk dynamics, CCS and cane and sugar yield. This understanding is important to address this problem either through genetic improvement and/or crop management. Secondly, it will help practical applications of crop growth simulation models to improve agronomic management.

Four different field experiments were conducted over two seasons (1997/98 and 1998/99) both in dry and wet tropical environments of northern Queensland, Australia. These field experiments were designed to quantify the separate effects of lodging, crop age and seasonal conditions on crop growth and yield accumulation. The data from the field experiments indicated that lodging was a major constraint to high yields in both the dry and wet tropical environments. There was no evidence that crop age or any seasonal factors were implicated in the slowdown of growth.

Prevention of lodging increased cane yield by 11 - 15%, CCS by 3 – 12% and sugar yield by 15 - 35%, at the final harvest in August/September, depending upon the extent and frequency of the lodging events. Apart from stalk death, lodging reduced the biomass and sugar content of the live stalks by reducing both the radiation interception and RUE of the crops. The economic losses from lodging were even greater due to the dilution effects from lower CCS of dead and rat-damaged cane. There was no evidence of any 'yield plateau' or 'stalk loss' when all the stalks, viz. live, dead and rat-damaged, were taken into account.

To evaluate the possible causes of the observed 'yield plateau' in the earlier studies, the growth and development of live stalks and the factors that contributed to stalk dynamics in these crops were re-examined. The crop biomass was re-estimated by taking into account the missing trash components, dead cane and any spatial stalk variations to better understand the yield slowdown in these studies. The re-analyses further strengthened the conclusions drawn from the current studies and offered plausible evidence that stalk death and stalk loss were the major factors that contributed to the 'yield plateau' in the earlier studies. The observations on the number of stalks suggested that spatial variations in the number of stalks were potentially a major factor that contributed to the 'stalk loss' in these studies.

The research implications of the conclusions from this thesis are considered in terms of the immediate actions that might be taken, and then the longer-term actions needed to improve productivity. Firstly, and most importantly, the longer-term implications that need to be addressed are to implement research to identify strategies to reduce lodging through crop management or breeding of lodging resistant varieties. For economic reasons, it is likely to be difficult to use changed agronomic management under Australian conditions. However, opportunities exist to improve sugarcane selection systems to select for lodging resistance. Overcoming lodging through breeding may take several years but the effects of lodging are sufficiently large to justify the research investment in this area. In the short term, there is potential to improve the accuracy and reliability of sugarcane crop growth simulation models. Secondly, again in the short term, it is important to avoid systematic bias or sampling errors in sugarcane field experimentation through improved sampling methodology.

To summarise, the field research reported in this thesis has identified and described the physiological basis of a major, and hitherto largely unrecognised, constraint to productivity in sugarcane crops in tropical Australia. The thesis has also reviewed and re-interpreted earlier research, to show that the earlier work is consistent with the main conclusions of the current research. The thesis concludes by suggesting ways in which future crop improvement research might try to overcome the effects of lodging on sugarcane productivity.

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Statement on sources declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

.... 04·06·03

(Gurmit Singh) (Date)

Chapter 1 Introduction

Sugarcane (*Saccharum* spp.) is a tropical plantation crop grown under diverse climates, throughout the world, from sea level to 1500 m at latitudes between 36.7 °N and 31.0 °S. Humbert (1968) described the ideal climate for sugarcane as a long, warm growing season and a fairly dry, sunny, cool but frost-free ripening and harvest season free from hurricanes and typhoons. The Australian sugar industry is located in five discontinuous regions, separated by areas of unreliable rainfall or unsuitable soils, along the eastern coastline between latitudes 16.49 °S and 29.48 °S (Kingston *et al.*, 1995). Climate in the production zones ranges from wet tropical to sub-tropical. Recently, the industry has expanded in the dry tropics (15.65 °S), in the Ord River irrigation area, Western Australia and in the Atherton Tableland region of north Queensland. Within this wide range of environments, different radiation and temperature regimes determine crop yield potential, which is then modified most significantly by moisture regimes determined by rainfall and irrigation (Muchow *et al.*, 1997a). From the productivity trends, it is evident that both breeding and agronomy have played an important role in increasing the productivity and profitability of the Australian sugar industry by identifying constraints to crop yield, and opportunities to overcome these constraints (Berding *et al.*, 1997; Garside *et al.*, 1997).

Recent research has shown that large lodged crops of sugarcane experience a marked slow-down in cane and sucrose yield accumulation prior to the normal time of commercial harvest, i.e., in winter months (Muchow *et al.*, 1994a; Muchow *et al.*, 1995; Robertson *et al.*, 1996). Cane yield may be as much as 40% below that expected from computer simulation models using weather data. This apparent ‘foregone’ yield represents a significant loss to the industry. Similarly, well-grown crops of sugarcane in the wet tropics frequently experience low mill commercial cane sugar (CCS) content. A recent industry analysis (Leslie and Wilson, 1996) suggested that this declining trend in CCS in the wet tropics was associated with several factors which increase the extraneous matter (EM) delivery to the mills, including lodging and stalk deterioration. Low CCS greatly reduces industry profitability because it increases harvesting, transport and milling costs per tonne of sugar produced. Growers are particularly concerned with low CCS since the current sugar pricing formula used for distributing revenue from sugar sales between growers and millers in Australia means that lower CCS tends to affect growers' incomes more so than millers'.

Various explanations of this yield accumulation slow down include: stalk death and damage by lodging (Das, 1936; Muchow *et al.*, 1995), low temperatures or chill injury (Grantz, 1989; Kingston *et al.*, 1995), and crop age (Das, 1936; Borden, 1945 and 1948; Gosnell, 1968; Muchow *et al.*, 1997). Other explanations for the yield accumulation slowdown may be a source limitation, i.e., whole canopy photosynthesis (reduction in radiation interception) due to the disruption of canopy architecture as a result of lodging. All these effects have been reported in other crops in different situations and some of the physiological processes involved have been described for different species (e.g. Cooper, 1971; Duncon and Hesketh, 1968; Monteith, 1977a; Pinthus, 1973).

Despite the possible importance of the issue, and the suggested role of lodging and stalk deterioration on productivity under Australian conditions, no research results were available to confirm or quantify the adverse effects of lodging, or to determine how important it is in relation to other possible causes.

1.1 Industry significance

The indirect losses due to increased extraneous matter and harvesting costs, resulting from lodging, may be significant and a greater focus on lodging in sugarcane breeding programs is justified (Jackson *et al.*, 1999). However, it was considered important to quantify the direct effects of lodging and other factors to clarify the causes of the apparent growth slowdown in an appropriate way.

Therefore, the aim of this study was to identify constraint(s) to the production of biomass and sugar in large, lodged cane crops. This understanding is important for two main reasons. Firstly, any attempt to address the problem of slow-down in yield accumulation, either through genetic improvement and/or crop management, would clearly benefit from the identification of causal factor(s). For example, if lodging is a major constraint then appropriate modifications to current sugarcane breeding programs may be made. This could include changes in the design of selection trial plots or the use of lodging resistance as a selection criterion in the selection index with other economically important traits such as cane yield and CCS. Selection of shorter varieties with large number of thick stalks and high CCS and cane yield may represent a better ideotype for pure stands than varieties with tall, thin stalks.

Secondly, knowing the cause of slowdown through a better understanding of the plant responses would also help practical application in crop growth simulation models and in agronomic research generally. Presently, crop growth simulation models accommodate the growth slowdown effect through direct loss in stalk numbers (Keating *et al.,* 1999). Any attempts to improve the model capabilities and the prediction of yields outside known experience, without any knowledge of the actual cause(s) or associated physiological processes of the slowdown, would be of unknown and questionable reliability. For example, if the cause is lodging, then earlier planting or ratooning under high yielding situations may lead to little or no difference in the final yield because the crops may simply lodge earlier compared with the normal planting/ratooning. However, if in fact the cause were a seasonal factor (e.g. onset of winter or low temperatures), then earlier planting or ratooning would be expected to provide higher yields because there would be a longer duration of growth before the slowdown in growth occurred.

Given the above issues, the research reported in this thesis aimed to identify the factor(s) causing this growth slowdown and associated mechanisms affecting the process of yield accumulation. Based on this knowledge, suggestions are then able to be offered on appropriate solutions such as breeding and/or agronomic management.

1.2 Aims of the research project

The possible explanations/hypotheses behind the observed slowdown in biomass and sugar yield accumulation are:

i. A direct loss of aboveground biomass occurs due to the breakage, death and rotting of stalks.

ii. Disruption of canopy architecture due to lodging, which affects light interception and ultimately reduces the canopy photosynthesis or radiation use efficiency (RUE) of the crops.

iii. Potential crop growth rate/stalk elongation is decreased directly by the influence of environment (e.g. low temperature) or in relation to changes in crop development (increased age) resulting in sink limitations.

This PhD study therefore initially aimed to discover what causes the growth slowdown effect, and then investigated the underlying mechanisms, i.e., to examine the separate effects of season (onset of winter conditions), crop age/size, and lodging in causing the slowdown in yield accumulation. With these aims, the present study was planned with the following specific objectives:

1. To determine what factor(s) cause large and lodged crops to slow down biomass production and sucrose accumulation, in some cases, well before the harvest, even when environmental conditions appear to be suitable for high growth rates.

2. To interpret and explain the effect of the identified factors on net growth and death processes as well as on stalk and sucker dynamics, cane yield and CCS.

3. To make suggestions on how the identified constraints to yield might be best addressed via breeding and/or management options. In, particular, if lodging were found to be an important constraint, alternative methods of selecting varieties for high-yielding environments may be appropriate.

As a pre-requisite to designing field experimental approaches to address these objectives, the literature on factors affecting the growth, biomass and sugar accumulation of sugarcane crops are reviewed in the following chapter, together with research on how similar issues have been explored in other crops.

Chapter 2 Literature review

2.1 Introduction

The purpose of this thesis was to study cane growth and development patterns in relation to lodging, crop age and seasonal factors, with the aim of identifying the major constraint(s) to productivity and then suggest possible solutions.

The rates, at which sugarcane produces dry matter, and the partitioning to sucrose, both depend on many environmental and physiological factors. The following review first provides an overview of the physiological determinants of economic yield in sugarcane and then describes briefly the effects of lodging, crop age and seasonal factors on crop growth and sugar accumulation. In some cases, information relating to the effects of such constraints on productivity has also been drawn from studies of other crops. However, where possible, the review is confined to sugarcane.

2.2 Overview of physiological determinants of economic yield

An important function of crop physiological research is to quantify the role of various growth processes and climatic and crop management elements contributing to yield variation. The yield accumulation in field crops may be considered in terms of use of limiting resources (e.g. radiation, nutrients and water), efficiency of converting these resources to assimilate and partitioning of the assimilates to the economic yield (Monteith, 1977). To maximise the yield, crops must optimise each of the steps in the acquisition and conversion of the resources to assimilate, and the allocations of assimilate to economic yield. Yield accumulation in sugarcane can be analysed by regular sampling of the crop throughout the growing season.

2.2.1 Components of yield in sugarcane

Evensen *et al.* (1997) noted that the commercial production of sugarcane is based on the fresh weight and sucrose concentration of millable stalks (mature cane). Consequently, the yield of all crop components is not routinely measured on a dry matter basis. At the simplest level, the physiology of yield accumulation is usefully analysed as production of biomass and the partitioning of biomass to economic yield (Squire, 1990).

Many early studies in Hawaii (Ayres, 1930; Moir, 1930; Das, 1936; Borden, 1942, 1945, and 1948) have reported time-trends of biomass accumulation in sugarcane. From a re-analysis of these studies, Evensen *et al.* (1997) concluded that often the dead leaf or trash component was not recovered, making comparison of biomass accumulation across experiments difficult. Furthermore, below-ground (stool + roots) biomass was rarely measured. Thomson (1978) reviewed several biomass experiments on sugarcane conducted between 1962 and 1970 in South Africa and estimated the proportions of trash (dead leaves + foliage) and millable stalks. He concluded that the fraction of millable stalks ranged from 0.59 to 0.71 for different cultivars.

Muchow *et al.* (1993) measured sugarcane biomass accumulation under irrigated and high-nutrient conditions at Macknade in tropical Australia and standardised the sampling procedures to record fresh weight, biomass and sucrose accumulation throughout the growth period. The aboveground biomass production was analysed by partitioning into four different yield components, viz., green leaves (blades), cabbage (immature stalk and green sheaths), millable stalk and trash (dead leaves and sheaths). Robertson *et al.* (1996) used the procedures described by Muchow *et al.* (1993) to measure the time-trends of biomass accumulation in plant and ratoon crops of sugarcane under irrigated and high-nutrient conditions at Macknade (Australia). They reported that during the early growth period (before millable stalk fractions were present), green leaf and cabbage components constituted about 0.5 – 0.6 and 0.4 of the above ground biomass respectively with a negligible proportion of trash components. However, with increase in biomass production, millable stalk fractions increased while the fractions of green leaf and cabbage declined exponentially. The fraction of trash remained below 0.1 over the entire range of biomass levels. They further concluded that at high levels of biomass (above 5000 g m^{-2}), about 0.8 was present as millable stalk, 0.1 as green leaf, 0.05 as cabbage and 0.05 as trash irrespective of crop class and cultivar. The fraction of millable stalk was dependent on crop age, the level of biomass production and the extent to which trash could be recovered. One of the reasons for a higher stalk fraction and a lower trash fraction in these experiments than the other experiments was the underestimate of aboveground biomass by about 15% (Evensen *et al.*, 1997). The aboveground biomass was underestimated because of incomplete recovery of the senesced leaf materials in these experiments.

Recently, Evensen *et al.* (1997), from field experiments under drip irrigation in Hawaii, reported that during early growth (<6 months) the below-ground biomass comprised up to 17% of the total biomass. This is higher than the 10 – 15% normally recorded for annual tropical crops (e.g. Squire, 1990). Furthermore, Evensen *et al.* (1997) observed that from 12 to 24 months, the fraction of below ground biomass was relatively stable and of similar magnitude (0.11) to that reported in early studies (Van Dillewijn, 1952). However, under certain conditions, soil compaction as a result of mechanical harvesting can reduce the fraction of below ground biomass by restricting the root system (Trouse and Humbert, 1961).

2.2.2 Canopy development and radiation interception

Intercepted radiation (*Si*) is the difference between the solar radiation received at the surface of the canopy, *S*, and that transmitted to the soil (Squire, 1990). Intercepted radiation is usually measured by arrays of solarimeters. The incoming radiation itself varies much throughout the tropics. Seasonal means of total solar radiation, in the wavelength range 0.4 - 3.0 μm, range from 17 MJ m^{-2} day^{-1} in the wet tropical regions to more than 24 MJ m^{-2} day^{-1} during cropping seasons in some dry tropical regions (Muchow *et al.*, 1991). Therefore, canopies are usually best compared, not by intercepted radiation (*Si*) itself, but by the fraction *Si*/*S* (termed as fractional interception, *fi*). For a given canopy, this fraction is little affected by the absolute value of *S*, so is useful for modelling dry matter production (Squire, 1990).

2.2.3 Biomass accumulation and partitioning

Biomass production, over time, can be considered as a function of the amount of radiation intercepted (*Si*; MJ m^{-2}) and the RUE of the crop (Monteith, 1977). Hence, biomass production in sugarcane can be expressed, in terms of a physiological framework, as:

$$\text{Biomass (g m}^{-2}\text{)} = S \times fi \times \text{RUE} \qquad \text{(i)}$$

where,

S = solar radiation (MJ m^{-2});

fi = fraction of radiation intercepted by the canopy; and

RUE (g MJ^{-1}) = Δ biomass (g m^{-2}) / radiation intercepted (MJ m^{-2}).

The amount of radiation intercepted is determined by the crop duration and consequently the cumulative incident solar radiation, and by the fraction of the incident radiation that is intercepted (*fi*) as determined by the leaf area development and the light extinction coefficient (*k*).

In sugarcane, yield is measured as cane yield, either on a fresh or dry weight basis. Components of biomass production in sugarcane can be dissected as follows:

Aboveground biomass (g m^{-2}) = millable cane biomass (g m^{-2}) + green leaf biomass (g m^{-2}) + dead leaf biomass (g m^{-2}) + cabbage biomass (g m^{-2})..................(ii)

where,

Millable cane biomass (g m^{-2}) = above ground biomass (g m^{-2}) × proportion of cane biomass in above ground biomass (%)..(iii)

or

Millable cane biomass (g m^{-2}) = cane yield (g m^{-2}) × cane dry matter content (%) ....(iv)

2.2.4 Sugar yield accumulation

The ripening process of sugar accumulation or maturity is partly a varietal character, giving rise to relatively 'early', 'mid-season' and 'late' maturing varieties. However, the process is greatly affected by weather conditions (temperature and solar radiation) and the cultural practices (crop age and management such as fertilizer rates, irrigation and lodging etc.) followed. In many countries (e.g. Australia, India) low winter temperature dictates the end of the growing season and the harvest period is adjusted accordingly. In tropical and semi-tropical areas, where either the temperature does not become low enough for excellent ripening or, as in Hawaii, where the economics of the industry dictate harvesting year-round, ripening has traditionally meant 'drying off' in the irrigated plantations or chemical ripening (Nickell and Meratzki, 1970).

Sugar yield is commonly measured commercially as the product of cane yield and the cane fresh weight sugar concentration. In Australia, the cane fresh weight sugar concentration is measured as CCS (BSES, 1984). Thus, sugar yield can be described as:

$$\text{Sugar yield (g m}^{-2}) = \text{cane yield (g m}^{-2}) \times \text{CCS (\%)} \ldots\ldots \text{(v)}$$

Under commercial situations, a large amount of extraneous matter (EM) or trash accompanies cane supply to the mill, which has a dilution effect on the mill CCS (Wilson and Leslie, 1997; Crook *et al.*, 1999). These CCS reductions can be much more in lodged crops due to additional EM as a result of lodging (Jackson *et al.*, 2000). Thus:

$$\text{Sugar yield (g m}^{-2}) = \text{cane yield (g m}^{-2}) \times \text{CCS mill (\%)} \ldots\ldots \text{(vi)}$$

where,

$$\text{CCS mill (\%)} = ((\text{CCS cane (\%)} \times \text{wt of cane}) + (\text{CCS trash (\%)} \times \text{wt of trash})) / (\text{wt of cane} + \text{wt of trash}) \ldots\ldots \text{(vii)}$$

In large and lodged crops, dead cane may constitute a significant proportion of stalk numbers (Muchow *et al.*, 1995). The low sugar concentrations of dead cane (Kenny and Komen, 1957) further have a dilution effect on CCS of cane, thus:

$$\text{CCS cane (\%)} = ((\text{CCS live cane (\%)} \times \text{wt of live cane}) + (\text{CCS dead cane (\%)} \times \text{wt of dead cane})) / (\text{wt of live cane} + \text{wt of dead cane}) \ldots\ldots \text{(viii)}$$

2.2.5 Stalk dynamics and yield accumulation

In high-yielding sugarcane crops, the stalk dynamics play an important role in determining the yield variability depending on the extent, weight and size of dead stalks and suckers (Borden, 1945 and 1948; Muchow *et al.*, 1995). Final cane yields, which constitute live and dead cane from both the primary and secondary stalk classes, can be expressed as:

Cane biomass (g m^{-2}) = wt of live stalks (g m^{-2}) + wt of dead stalks (g m^{-2}) + wt of suckers (g m^{-2}) .... (ix)

where,

Wt of live stalks (g m^{-2}) = wt per live stalk (g) x number of live stalks (m^{-2})
Wt of dead stalks (g m^{-2}) = wt per dead stalk (g) x number of dead stalks (m^{-2})
Wt of suckers (g m^{-2}) = wt per sucker (g) x number of suckers (m^{-2})

Finally, analogous to the interpretation of grain yield as the product of grain size and grain number, stalk biomass of cane can also be measured on the basis of individual stalk growth rate. Hence, the biomass production can also be expressed in terms of change in stalk numbers and individual stalk growth over time as:

Biomass (g m^{-2}) = stalk growth rate (g day^{-1}) × Δ stalk number (per m^2) x crop duration (days) ....(x)

The above framework can be used to assess crop yield potential with better estimates of the amount of radiation interception and RUE of the crops. However, regular growth analysis samplings are required to quantify the effect of various factors on key growth processes such as stalk numbers and stalk growth rate, leaf canopy development, fresh weight accumulation, biomass accumulation and partitioning and sucrose content and accumulation.

2.3 Sugarcane lodging and yield accumulation

2.3.1 A brief overview of lodging

Lodging refers to the 'falling over' of the crop due either to stem or root failure. It is an important problem that all plant breeders, particularly those connected with the cereals, have to contend with, in their attempts to secure the maximum yield potential of varieties. Because of its economic importance, lodging has been extensively studied in many crops and ongoing attempts have been made to combine lodging resistance with other desirable agronomic characters in many plant breeding programs (sugarcane: Amaya *et al.*, 1996; Berding and Bull, 1997; maize: Carter and Hudelson, 1988; wheat: Fisher and Stapper, 1987; Tripathi, 1999; barley: Hanson *et al.*, 1985; soybean: Cooper, 1971 and 1985).

Lodging in sugarcane is a complex phenomenon and it is important to realise that it differs in certain essential features from what is observed in small cereals. Lodging in small cereals generally refers to a condition where the crop at or near maturity gets 'laid over' either completely or in part. Thus lodging is often only a problem at harvest. This feature is associated with the morphological architecture in cereals, which may include limited tillering (or its complete absence in some), a hollow thin stem and the fixed number of internodes on the stalk and grain weight at the top of the stems (Pinthus, 1973).

In sugarcane, the profuse tillering with complex underground branching and the solid stem having internodes of varying lengths and diameters, are factors that render the lodging phenomenon in this case as belonging to a special class itself. Das (1936) asserted that lodging in sugarcane might be associated with less lignified and sclerenchymatous tissue. Nagi and Mishra (1960) concluded that the character for 'erectness', or 'lodging' seemed to be an inherent character of the clones and can be influenced to some degree by the external factors. However, in sugarcane crops, the canopies generally become erect again some weeks after lodging, probably due to geotropic stimulus responses (Dutt and Ethirajan, 1954; Humbert, 1968).

Following irrigation or rain and wind, lodging is very common in well-grown crops of sugarcane. It is quite widespread throughout the Australian sugar industry (e.g. on an average, more than 80% in the north Queensland mill areas and the Burdekin can lodge) and can be highly variable from season to season depending on the prevailing weather conditions (King, 1956; Buzacott, 1965; BSES, 1980).

2.3.2 Characterisation of lodging in sugarcane

Lodging in sugarcane is a term usually applied to include a range of conditions, from few canes in a stool inclining at various angles to the vertical (good sprawling) to the complete lying flat of entire rows of cane, and in some cases uprooting of whole stools, over large portions of the field. In sugarcane, lodging can be classified under the three different categories of stalk lodging/bending, root lodging and stool tipping.

Stalk lodging/bending is a state of inclination of few to all stalks from the vertical, due to a gradual bend in the middle internodes, but with the roots still intact in the ground. In this situation, the stalks after making an erect growth for some time tend to fall away from the vertical (Dutt and Ethirajan, 1954). Stools of stalks thus lose their compactness, with the tillers reclining at various angles. This phenomenon is thought to be more common in varieties with thin and elastic canes, on the assumption that they cannot support the weight of heavy tops, especially after rain that can result in about 20% increase in the weight of tops (Pinthus, 1973; Easson *et al.*, 1993).

Root lodging refers to straight and intact stalks leaning from the vertical (Fouere *et al.*, 1995). In general, root lodging is a predominant type of lodging occurring in cereals as a result of reduced plant anchorage under wet conditions of rain or irrigation (Pinthus, 1973). It may occur in large sugarcane crops (>150 t cane ha^{-1}) under irrigation, as well in relatively small crops (<80 t cane ha^{-1}) in wet conditions. Khanna (1951), under rainfed conditions in Bihar (India), found an association between poor root development in sugarcane and lodging. He further stated that ratoon crops, which possessed a well-developed root system, exhibited less lodging compared to the plant crop.

In some circumstances, during storms when winds are very high, whole stools may fall over without any perceptible bend anywhere on the stalks (Dutt and Ethirajan, 1954). Some varieties have relatively shallow root systems and stools are often partially up-rooted, resulting in the death of parts of root system and some stalks that were largely nourished by those roots (Humbert, 1968; BSES, 1992). This form of lodging is called stool tipping. However, in wet tropical environments, stool tipping may have an association with the occurrence of *Pachymetra* root rot disease (Magarey, 1994).

Thus lodging in sugarcane may be defined as the phenomenon by which individual tillers in a stool or the whole stool go away from the vertical, at various periods during growth, and is the result of the interaction of many complex factors (Nagi and Mishra, 1960; Skinner, 1960). Prevailing environmental factors, though they may not be actually responsible for lodging, may accelerate the process and reveal the inherent weakness in a variety.

Lodging resistance of all varieties is at a minimum when root anchorage is reduced by saturated 'soft' soil conditions, and this is the time when wind causes lodging. Some small ratoon crops tend to lodge, even in well-drained soil, and this may be due to the fact that in some varieties the root system of a ratoon crop is shallower than that of a plant crop. It is suggested that physical lodging resistance depends mainly on the type and size of the root system (Skinner, 1960).

Many anecdotal reports suggest that lodging is an important factor in the mortality of cane stalks harvested at two or more years of age (Das, 1936; Humbert, 1968; Muchow *et al.*, 1995). However, Van Dillewijn (1952), reviewed several studies conducted under Hawaiian conditions and concluded that tasselling and water stress were other factors that resulted in significant amounts of death of the primary stalks between 18 to 24 months of crop age. Lodging in different directions from successive storms is particularly damaging since the extended movement usually results in severe breakage and smothering effects, which can cause stalk death. In the case of varieties that are brittle, tops snap in windy conditions often resulting in death of the stalks. This loss is serious, since often the taller and most vigorously growing tops are the ones to be lost.

Many current varieties in Australia seem to have a high propensity to lodge (BSES, 1980; Berding and Bull, 1997). Up to now, the industry has tended to accept varieties prone to lodging, perhaps partly because lodging generally signifies a heavy tonnage (many varieties with high cane yield lodge), and perhaps also a view that there is little that may be done about it. Also, the development of modern harvesters, which can cope with heavy lodged crops, has tended to reduce the need for erect cane in Australia compared with prior to 1970 when hand harvesting was practised. The harvesting of recumbent and tangled cane crops had always attracted special cutting rates to compensate labour for the slower output of tonnage (King, 1955). Lodging resistance had a higher priority in sugarcane breeding programs in Australia prior to the widespread introduction of machine harvesting (King, 1955; Skinner, 1960). Given the relative ease now of harvesting severely lodged crops mechanically, it is possible that lodging effects on yield and sugar content are not as well understood. In research, quantitative documentation of lodging effects on yield in sugarcane has been largely overlooked probably due to, at least partly, the difficulty of measuring such effects free of potential confounding influences. Many observations in the literature are anecdotal, but worth examining for their breadth of views.

2.3.3 Lodging and biomass accumulation

An association has frequently been made between lodging and stalk breakage/stalk smothering (Das, 1936; Shaw, 1964; Singh, 1975; Ahmad, 1997). Physical damage (stalk breakage and smothering) renders the stalks prone to entry of disease, leading to microbial decomposition and loss of stalk biomass leading to loss of stalk weight and total cane yield (Martin, 1939; Arceneaux, 1941; Humbert, 1968). Lodging also makes stalks more susceptible to rat-damage, resulting in further losses in cane and sugar yields (Humbert, 1968; Porquez and Barredo, 1978; Roach and Evans, 1979; Sayed *et al.*, 1980).

There are reports claiming an association between lodging and yield losses due to stalk death and loss of stalk numbers (Muchow *et al.* 1995; Robertson *et al.*, 1996). But it is unlikely that dead stalks with cane could 'disappear' during the course of an experiment. The apparent net 'loss' of stalks following lodging may be a result of spatial sampling variations or the difficulties of recovering stalks following lodging. In these studies, this cannot be confirmed due to unavailability of data on stalk numbers before lodging.

Studies in India indicated an increase (12 – 17 t ha^{-1}) in a cane yield of 100 - 125 t ha^{-1} when lodging was prevented by using different propping methods (Parthasarathy, 1970). However, in these reports, there was no clear analysis ruling out any possibility of involvement of other potential confounding factors such as variations in stalk numbers and growth environments etc. In an experiment in which two sugarcane varieties were artificially lodged, Vaidyanathan (1954) assessed the extent of loss in yield and quality of the stalks due to lodging compared to the erect stalks. The crops were subjected to mechanical lodging by means of fixing bamboo on a regular basis, for a period of four to five months, across the plant rows making the plants level with the ground surface. Compared with the erect stalks, lodging reduced the average stalk weight by 13.5% and 14.6% in both the varieties. He further reported that variable amounts (6.3% – 19.9%) of stalk damage/breakage were observed due to lodging in both the varieties under study. One of the concerns with artificial lodging of the crops in this study is that artificial lodging varies from the natural lodging in several aspects and so does not reflect the real situation. In the case of natural lodging in sugarcane, the crops generally re-establish canopies, as tops of the lodged crops become erect again a few weeks after lodging. The extent of stalk damage or breakage may also be lower under natural conditions compared with the artificial conditions. Hence, due to these confounding factors, it is impossible to draw any firm conclusions based on this study.

Sharma and Rao (1978) analysed stalk samples (10 stalks per sample) taken in duplicate from perfectly erect and completely lodged areas of a field to assess the extent of losses due to lodging. From the comparisons of lodged and erect cane, they recorded reductions in weight of green tops and stalks up to 45% and 25% respectively due to lodging. They further observed varietal differences (10 - 35%) in yield reductions under lodging. Similarly, Ahmed (1997) studied cane yield and quality characteristics of lodged and non-lodged stalks drawn from three different fields after 100 days of lodging. Compared with non-lodged stalks, lodging reduced the cane length, thickness and weight by 9.1, 7.9 and 21.8 % respectively resulting in 21.5% reductions in final cane yield. In both of these studies, the samples of lodged and non-lodged stalks were drawn from different parts of the fields. Other factors such as soil nutrient and water status etc. might have had some impact on these results. Areas where lodging occurred most could have tended to be those where growth conditions were otherwise most favourable. These studies are of little value for quantifying effects of lodging because the effects of lodging are not separated from potential confounding factors. There is not any unequivocal field study or experiment that has shown that prevention of lodging results in higher yield of sugarcane.

Experiments with other field crops have shown that lodging is a clear constraint to yield potential under high yielding conditions. In soybeans, Cooper (1971) showed that prevention of lodging by using a wire grid system increased yields by up to 23%. Breeding of semi-dwarf soybeans to overcome this lodging barrier to yield, combined with modified crop management, led to higher yield potential in soybean under high-yielding environments (Cooper, 1985).

Similarly, Fisher and Stapper (1987), from various field experiments on wheat, reported that prevention of lodging by a supportive mesh increased total biomass production. Culm lodging of wheat to an almost horizontal position reduced the grain yield by 7 – 35% with lodging at the post anthesis period. They further concluded that yield losses from lodging could be variable depending on the time of lodging as well as the severity of lodging. Losses of as much as 40% of grain yield, resulting from lodging at early ear emergence were recorded in wheat grown in high-yielding cool, wet environments (Hay and Walker, 1989).

It has been suggested that the effects of lodging on yield can be due to its effects on crop growth rate. De Wit (cited in Van Dobben, 1966) calculated that less-favourable distribution of light amongst leaves following lodging could reduce post-heading growth in cereals by 200 g m^{-2} in the Netherlands. Hanson *et al.* (1985) also measured similar reductions in spring barley. Lodging is also known to be a major cause of yield losses in maize because of its direct effect on dry matter accumulation and indirect effects on harvesting operations (Carter and Hudelson, 1988).

2.3.4 Effect of lodging on sugar content

Lodging is not reported to have any direct influence on sugar accumulation processes. However, it can affect sugar content indirectly by stalk breakage and subsequent exposure to attack by micro-organisms causing the stalks to rot, and by re-growth of damaged stalks (Martin, 1939). In the case of mechanical harvesting, lodging decreases sugar yield through its association with the increased delivery of EM in the harvested cane (Leslie and Wilson, 1996). Under the wet-humid conditions of north Queensland (Australia), there is increasing evidence that lodging can lead to loss in sugar yield by lowering the sugar content and cane yields (Hurney, 1984; Muchow *et al.*, 1995; Garside and Nable, 1996; Pope, 1997; Hurney and Berding, 2000).

Other workers have reported a loss of both sugar content and sugar recovery in lodged crops (Srivastava, 1935; Khan and Basappa, 1960; Sharma and Rao, 1978; Sharma and Sharma, 1979; Ahmad, 1997; Hurney and Berding, 2000). In all of these studies, juice quality was analysed from samples of lodged and non-lodged stalks drawn from various parts of the fields without taking into account the potential confounding factors such as variations in growth environments and type and extent of lodging etc. Thus, the results of these studies are of limited value.

Lodging is reported to have reduced sucrose content by about 1.8% under Rhodesian conditions in southern Africa (Anon., 1970). But details of this study are not known, so it is impossible to comment on the conclusiveness of these results. Borden (1942) reported the results of a pot experiment, where half the numbers of pots were laid on their sides at 8 months after planting to simulate sugarcane lodging. After 5 months, it appeared that lodging had resulted in an average loss of almost 25% sugar, mainly due to lower sugar content in juice in the lower lodged section. These effects from lodging were not altered by increased nitrogen fertilisation. Similarly, in an artificially lodged field experiment, Vaidyanathan (1954) found up to 10% reductions in sucrose content due to lodging resulting in about 16 to 25% reductions in sugar yield. He further correlated the varietal differences in juice quality with different amounts of stalk damage/breakage. Damaged or broken stalks are known to have lower sugar content as compared to undamaged stalks (Arceneaux, 1941; Kenny and Komen, 1957).

However, the losses from lodging can be variable depending on the extent of lodging, i.e., degree of inclination from the vertical. Under controlled lodging in pot experiments, Parthasarathy and Narasimha Rao (1953) and Narasimha Rao (1958) assessed the sugar content of juice in relation to the degree of lodging and estimated that loss in sugar content in stalks lodged to 60° and more to the vertical, to be as much as 25%. They also reported that the loss in sugar content was not significant when lodging was less than 30° to the vertical.

2.4 Environmental effects on sugarcane growth and yield

Muchow *et al.* (1995) pointed out that the crop environment can be considered in terms of two components: the physical or abiotic environment, which includes the attributes of climate (temperature, radiation, and rainfall) and soil resource supply (water and nutrients); and the biological or biotic environment, which includes the attributes of fauna, flora, insect/pests and diseases. The impact of environment on crop yield is complex due to the interaction between these elements. This review is confined to the effects of radiation, temperature and soil moisture on yield accumulation in sugarcane.

2.4.1 Biomass accumulation

2.4.1.1 Analysis of radiation limited growth

Intercepted radiation is a major driving variable of crop production under high-input irrigated conditions. In the absence of stresses, crop growth rate is a linear function of the amount of radiation intercepted (Shibles and Weber, 1966; Muchow and Charles-Edwards, 1982), with the slope of the relation providing an estimate of RUE.

Monteith (1977) presented an analysis of the relationship between the accumulation of crop dry matter and intercepted solar radiation. He expressed the dry matter production, under ideal conditions, as the product of the cumulative radiation intercepted by the crop and the conversion efficiency of radiation to assimilate. It can be written as $DM = e \times fi \times SR$, where DM is the amount of dry matter produced, SR is the flux density of incident radiation, *fi* is fraction of light intercepted by the crop, and e is a conversion efficiency or RUE. Thus, RUE is a measure of how efficiently the radiation intercepted by the crop canopy is used to produce biomass. RUE and fractional interception, *fi*, are determined by crop physiology and management. These attributes though are greatly modified when the entire canopy is considered with the complexity of leaf arrangements and ages and the varying light environment within the canopy (Clements, 1940; Monteith, 1975; Kucharik *et al.*, 1998).

Robertson *et al.* (1996) noted that under high-input conditions, crop biomass accumulation can be analysed as a function of the radiation intercepted and RUE of the crop. Physiological factors contributing to differences in RUE include the inherent photosynthetic capacity of leaves, the balance between photosynthesis and respiration in the whole crop, and canopy extinction coefficients. Lawn (1989) pointed out that within the closed canopy, radiation is attenuated downwards with cumulative leaf area index

(LAI) in accordance with Beer's Law and the extinction coefficient (k) of the crops. The latter in turn depends on genotype, and, particularly prior to canopy closure, spatial arrangements of leaves and plants. Inman-Bamber (1991), by integrating light interception over the day, determined the 'k' value as 0.58 under South African conditions for sugarcane. However, other factors such as cultivar, starting time of crop and occurrence of water or nutrient stress also play an important role in the leaf area development of the crops and affect the value of extinction coefficient. Under Australian conditions, from the relationship between the fractional radiation interception and LAI, Muchow *et al.* (1994a) estimated a 'k' value of 0.38 for the cultivar Q96 and Muchow *et al.* (1994) calculated a 'k' value of 0.44 for the cultivar Q117. A 'k' value of 0.40 has been determined for maize and sorghum (Muchow *et al.*, 1990; Hammer and Muchow, 1991).

Statistical analyses have shown that sugarcane yield is positively related to solar radiation (Das, 1933; Stanford, 1963; Clements, 1980). Thomson (1978) under South African conditions, and Kingston *et al.* (1984) under Australian conditions at Ayr and Bundaberg, related biomass to the conversion of incident solar radiation and found that conversion efficiency varied with crop age and growth conditions. However, in these studies, the confounding factors such as differences in canopy development and the interception of radiation may have had an impact on the conversion efficiency of the crops.

There are very few studies that have measured RUE in sugarcane. Field experiments, conducted by Muchow *et al.* (1994a) and Robertson *et al.* (1996) under north Queensland conditions of Australia, in well-managed sugarcane crops have shown maximum values of RUE about 1.7 g MJ^{-1} based on net above-ground biomass. However, there are reports from Hawaii that maximum RUE of sugarcane approached 2.0 g MJ^{-1} and varied with crop age (Muchow *et al.*, 1997). The lower values of RUE for Australian crops may be due to the underestimate of trash components as not all the dead leaves were recovered in these studies (Evensen *et al.*, 1997). By assuming that trash accounts for 15% of the total biomass, then the RUE values were close to 2.0 g MJ^{-1} as estimated for Hawaiian crops by Muchow *et al.* (1997). The average RUE from planting to crop harvest in high yielding crops has been observed to be much lower (e.g. 1.37 g MJ^{-1}, Muchow *et al.*, 1994a) due to a slowing down in crop growth rates before harvest. Robertson *et al.* (1996) reported differences in biomass production between crop classes. They observed higher values of RUE in the plant crops (1.72 g MJ^{-1}) than in the ratoon crops (1.59 g MJ^{-1}) and assumed that this was due to differences in biomass partitioning between crop classes.

Robertson *et al.* (1996) further concluded that maximising early radiation interception and biomass accumulation would not necessarily lead to higher yield in an environment where biomass production reaches a plateau well before the final harvest. They observed cessation in biomass production about 300 days after planting/ratooning and 140 days before final harvest, which was associated with loss of live millable stalks rather than a cessation in growth rate of individual stalks. The crops continued to intercept radiation while on the biomass plateau, so that average radiation use efficiencies at final harvest were much lower than the maximum values.

2.4.1.2 Temperature effects on growth

Sugarcane is generally grown for periods of 12 months or longer, including through periods of the year when cool temperatures might be expected to limit growth in the subtropical regions. For instance, cool temperatures limit the photosynthetic rate in sugarcane (Bull, 1980), and hence radiation use efficiency. The development of the sugarcane canopy may also be considered as a process dependent on the emergence of tillers and leaves. Thus, canopy development depends on the rates of tillering, leaf appearance, and leaf extension and size of each leaf. Key physiological processes, which have been shown to be highly sensitive to temperature, are the rates of leaf appearance and development in cereals (Gallagher, 1979; Muchow and Carberry, 1989) and sugarcane (Glasziou *et al.*, 1965; Inman-Bamber, 1994; Campbell *et al.*, 1998). For instance, stalk elongation was delayed 100 days when sugarcane was subjected to 18°C instead of 30°C constant temperature (Glasziou *et al.*, 1965). The rate of leaf appearance in sugarcane also varies among different genotypes having similar base temperatures (Campbell *et al.*, 1998). Hence, in the absence of abiotic or biotic constraints, the main factor driving leaf area expansion is temperature (Ong and Baker, 1982).

There are reports that the terminal bud and leaves of sugarcane are killed by temperatures of -3.5°C, and entire aboveground stalks are killed at -5.5°C (Irvine, 1989).

Van Dillewijn (1952) and Humbert (1968) reported that temperatures below 7.1 °C adversely affect sugarcane growth. Inman-Bamber (1994), from a field study under South African conditions, concluded that the base temperature, at which sugarcane growth ceases, lay in the range of 10 – 15°C. However, under Australian conditions, Campbell *et al.* (1998) reported a lower (7.6 – 7.8°C) base temperature for leaf appearance in sugarcane. Robertson *et al.* (1998) has validated these values through incorporation into a crop growth model and comparison with field data.

Cool night and early morning temperatures, 14°C in the winter and 20°C in summer, significantly inhibited photosynthesis in sugarcane the next day (Grantz, 1989). Kingston *et al.* (1995), on the basis of Grantz' criteria, concluded that most districts in the east coast Australian sugar industry might expect some chill injury ranging from one month at Meringa (Cairns), through to three months at Ayr, four months at Mackay, five months at Bundaberg and seven months at Grafton.

Blacklow (1972) concluded that photosynthesis in C_4 plants increases rapidly with leaf temperature up to a maximum rate between 30°C and 40°C, and then at higher temperatures decreases rapidly. Lal (1974) reported that growth of young maize plants was inhibited when the soil surface temperature exceeded 35°C, a condition not uncommon in the tropics, particularly when the soil surface is dry. Similarly, Singh and Lal (1935) reported a gradual decline in the rate of photosynthesis in sugarcane above 34°C for several days at a time in the northern sectors of the Queensland industry. Others have suggested that the critical temperature above which internode growth is likely to be affected is 32.0°C (Van Dillewijn, 1952; Humbert, 1968). Thus longer periods of high temperature stress might be expected in the Ord River area, where mean maximum temperature exceeds 34°C from September to April.

Temperature has both direct and indirect effects on plant growth. Low soil temperatures reduce water uptake (Duncan and Cook, 1932) of plants and cell elongation may then be affected by minor levels of water stress (Hsiao, 1973). Temperature directly affects the rate of cell elongation (Peacock, 1976).

2.4.1.3 Soil moisture and plant growth

Several workers have reported a high positive correlation between the moisture content of the elongating cane and meristem, and the rate of elongation (Clements and Kubota, 1942; Clements *et al.*, 1952; Mallik and Venkataraman, 1958). Since growth is largely a process of cell elongation associated with uptake of water, a close relationship may be expected between the water content of the cane plant and its rate of elongation. Under irrigated conditions, stalk elongation declined sharply when the soil moisture levels fell below 29.0 per cent (Clements *et al.*, 1952). Sun and Chow (1949) have also reported a high positive correlation between rate of stalk elongation and rainfall under rainfed conditions in Taiwan.

Contrary to the findings of some others, Van Dillewijn (1952) reported that the stem grows at a uniform rate as long as the moisture content of the soil is above the wilting point and ceases to grow below wilting point. Singh and Singh (1966) reported that cane elongation is sensitive to both decreasing and increasing soil moisture levels.

More recently, Inman-Bamber and de Jager (1986) found that cane growth is highly sensitive to water stress as it reduced both stalk and leaf extension. The effect of water stress may be fully reversible. Water stress affects the development of cane and sucrose yields differently. Under moderate stress over a long period, leaf and stem elongation is reduced more than photosynthesis and dry matter content may rise sufficiently to offset the effect of the marked reduction in cane yield. Under irrigated conditions, water is usually withheld prior to the harvest to dry the field, to make it trafficable for harvesting (Robertson *et al.*, 1999a). However, severe water stress can result in stomatal closure, which can halt the increase in dry matter of stalks (Inman-Bamber and de Jager, 1988). Singels *et al.* (2000) measured biomass accumulation of the stalk and non-stalk components of well watered and water stressed sugarcane along with soil water content in a rainshelter facility and observed a reduction in biomass accumulation when relative soil water content dropped below 35% of available capacity.

2.4.2 Environmental effects on accumulation of sugars

Muchow *et al.* (1997a) pointed out that climatic factors (temperature, solar radiation, and rainfall) play an important role in determining the sugar content of cane. Further, they indicated that annual mean daily temperature decreases with increase in latitude. There is a similar trend for solar radiation, except at high rainfall sites, which may have reduced levels of radiation. Rainfall, amount and distribution, prior to and during the harvest season can influence CCS through cellular hydration of millable stalks. Higher CCS tends to be associated with lower rainfall (Russell *et al.*, 1991) and variation in CCS over the harvest season in different zones of a mill district has been related to rainfall (Muchow *et al.*, 1997a).

Temperature directly affects the rate of cell elongation (Peacock, 1976). However, it is generally believed that cool temperature promotes sugar accumulation because it reduces stalk elongation, and hence consumption of carbon, more than it reduces the production of carbon (Glasziou *et al.*, 1965; Wilson, 1975). Cool winter temperatures are regarded as an asset for the Australian sugar industry, which enjoys some of the best natural ripening conditions for cane in the world (Kingston *et al.*, 1995). The critical mean daily temperature to initiate sugar accumulation in cane is thought to be between 20 – 24°C (Yates, 1983). This is illustrated by data of Bull (1980), who showed that stalk elongation rates were more sensitive to decreasing temperature at temperatures below 25°C than the photosynthesis of a single leaf. Although low temperatures during winter promote sugar accumulation by reducing stalk elongation or growth and respiration, chilling temperatures (-2 to 15°C) can reduce sugar accumulation because of negative effects on photosynthesis (Ludlow *et al.*, 1992). Similarly, Liu and Kingston (1995) concluded that temperatures below 2.5°C do not favour sugar accumulation, and reduction in sugar content can occur if cane experiences frost or chilling temperatures.

Tropical grasses, including sugarcane, are highly efficient in utilization of sunlight (Burr *et al.*, 1957). Being a C4 plant, sugarcane may not be saturated by light as far as total photosynthetic production is concerned but in terms of photosynthetic efficiency, varieties differ considerably (Kortschak *et al.*, 1965). There is no evidence of any direct impact of solar radiation on sucrose content of cane, but the varied levels of radiation may have some effect on the sugar accumulation processes by modifying leaf photosynthetic rate and partitioning of photosynthates. There are reports that low CCS of Tully and Babinda farms is possibly associated with low levels of radiation due to shading from mountains and high cloud cover (Sturgess *et al.*, 1972; Liu and Kingston, 1993).

Soil moisture stress is also an important environmental stress that promotes sugar accumulation in rainfed sugarcane areas of Australia and many other countries. In irrigated sugarcane production in most parts of the world, water is usually withheld prior to the harvest to dry the field to raise both sucrose concentrations of the cane and the sucrose yield (Inman-Bamber and de Jager, 1986; Robertson *et al.*, 1999a). However, the optimum length of the drying-off period depends on the rate of development of crop water deficit and the associated changes in sucrose content, cane yield and the sucrose yield. The imposition of water deficit through drying-off of sugarcane has a number of effects on crop productivity. The most economically important of these act in opposition, i.e., the reduction in cane yield through reduced carbon assimilation, versus the increase in sucrose concentration brought about by an increased partitioning of dry matter within the plant towards sucrose (Inman-Bamber and de Jager, 1988). Generally, drying-off is more often associated with an increase in sucrose concentration or dry matter content than with a reduction in cane yield (Robertson and Donaldson, 1998; Singles *et al.*, 2000). However, the severity of drying-off required to produce maximum return will depend on the trade-off between the increase in sucrose concentration and reduction in cane yield (Robertson *et al.*, 1999).

2.5 Effect of crop age on sugarcane growth and yield

Sugarcane is grown in a range of production systems throughout the tropics and subtropics, where the duration of crop growth can vary from 9 to 36 months. The age of cane at harvest depends on the climate, soil and cultural practices such as the variety, time of planting, irrigation, fertilisation and plant protection measures (Martin, 1939). The climate plays a major part in determining the timing of harvest, economic considerations such as planting and harvesting costs and farm management schedules are also important. May and Middleton (1954) did a statistical analysis of historical Hawaiian yield and economic data, and concluded that the optimum age of harvest is not fixed, and that individual plantations should determine harvest age based on historical experience or periodic crop sampling. Inman-Bamber (1991) used a crop simulation approach to determine optimum age of harvest under rainfed conditions in South Africa and concluded that several factors such as pests and diseases, flowering, severe drought, water logging and frost play important roles in determining the optimum age of harvest.

2.5.1 Effect of crop age on biomass accumulation

There have been relatively few field studies on the processes of yield accumulation in sugarcane to examine effects of crop age on growth rates. Gosnell (1968), from field experimentation under rainfed and irrigated conditions of South Africa, observed a reduction in cane yield increment and crop growth rate with increasing crop age, irrespective of prevailing environmental conditions. Increasing age reduced elongation rate, foliage production and LAI, rate of leaf emergence, length of the top visible dewlap (TVD) sheath, tissue moisture contents, chlorophyll content of leaves and a reduction in the efficiency of light utilisation at the canopy level. Other factors such as lodging of the crops and late season nutrient deficiency and moisture stress might have had some impact on the above results. However, du Toit (1956) and Baver (1963) found relatively little effect of increasing age, at least up to 21 months, on sugarcane growth rates.

Rostron (1972), in two-year crops ratooned at different times of the year in South Africa, tried to separate the confounding effects of season and age by sequential harvest throughout the year. Significant differences were observed in the final cane yield 72 weeks after ratooning. This was related to lodging in some of the crops and it was suggested that crops that lodge at the beginning of summer should not be allowed to carry over for harvest in the following season. Similarly, Lonsdale and Gosnell (1975) associated the decline in growth rate after 12 months of age with increased lodging of the crops. Evensen *et al.* (1997) indicated the optimum age of harvest for irrigated crops under Hawaiian conditions was 18 months. While there were cultivar differences in yield accumulation during the first 12 months of growth, there was little difference in final yield at 18 to 24 months.

Generally, in sugarcane, the main effects of increasing age on stalk growth and development can be viewed in terms of radiation interception and utilisation, and stalk dynamics, i.e., changes in stalk numbers and their development.

2.5.1.1 Crop age and radiation interception

In Australia, sugarcane is planted in wide (usually about 1.5m) rows to accommodate increasing levels of mechanisation and sizes of the machinery used for various field operations (Ridge and Hurney, 1994). The biomass accumulation during early growth would be expected to be lower due to the longer period for closure of the canopy (Irvine *et al.*, 1980; Muchow *et al.*, 1994a; Bull and Bull, 1996).

Since leaf area development is sensitive to temperature (Muchow and Carberry, 1989; Inman-Bamber, 1994) and cultivars differ in early leaf area development (Muchow *et al.*, 1997), early biomass accumulation would vary with planting date and crop cultivars. Genetic differences in leaf area development are also quite clearly evident in breeding nurseries up to 6 or 7 months of age (T. Morgan, CSR Technical Field Department; personal communication).

Muchow *et al.* (1997) examined biomass accumulation in sugarcane under Hawaiian and tropical Australian conditions and found that RUE of the canopy was much less for growth beyond 12 months than in the first 12 months with maximum value of 2.0 g MJ^{-1}, i.e. biomass accumulation beyond 12 months was not related directly to radiation interception. One of the reasons for these lower growth rates during the second year may be due to confounding effects of lodging on RUE of the crops, since severe lodging events were observed in all these crops in the second year of growth. Similarly, Inman-Bamber (1994a) in Natal, South Africa, observed that stalk elongation and dry matter production slowed down with age due to decline in leaf production and hence leaf area index. However, it was acknowledged that the effects of seasonal factors such as low temperature, severe water stress, flowering and lodging were confounded with crop age in these experiments.

2.5.1.2 Stalk growth and dynamics with age

In sugarcane, where the vegetative stalks comprise the economic yield, the yield limit in warm tropical environments may be strongly determined by the duration of crop growth in relation to phenological development of a variety. Sugarcane growth may be considered in terms of stalk elongation, but always involves increase in dry matter as well as increase in size and weight of the stalks. These components do not necessarily run parallel to each other. During water stress or low temperature, stalk elongation may be affected more than photosynthesis (Glasziou *et al.*, 1965; Inman-Bamber and de Jager, 1986), resulting in an increase in dry matter content.

Singh and Lal (1935) found that the young and the mature leaves showed a high and a medium RUE respectively, while the old ones exhibited a low photosynthetic rate. However, the age of a plant as a whole influences assimilation in two different ways. First, there is a direct age effect as the rate of assimilation per unit area of leaf surface increases from the early stages up to a certain stage of development and decreases during the period of ripening-off (Hartt and Burr, 1967). Secondly, there are indirect effects on radiation interception through the changes in LAI due to senescence with increased age (Inman-Bamber, 1994a). Marked evidence of a decline in net assimilation rate (NAR) with increasing age has also been reported in a range of other crops (Thorne, 1960). Bull (1969) detected photorespiration in a leaf attached to an 18-month-old sugarcane plant and found that this leaf was significantly less efficient than similar leaves from a young plant and also displayed a greater resistance to CO_2 transport. As sugarcane is often grown in regions of high radiation intensity, this effect could be quite common where the canopy comprises a large area of 'old' leaves, e.g. when flowering has occurred.

The shoot population in sugarcane increases rapidly up to a certain period, depending on time of planting, then declines as the canopy closes-in, and changes little thereafter (Gosnell, 1968; Bull 1975). Similarly, under tropical conditions of Australia, Garside *et al.* (2000) observed peak shoot numbers (>15 shoots m^{-2}) at three months after planting and then these numbers stabilised at 8 - 9 stalks m^{-2} within 5 months after planting. However, Das (1936) observed a reduction in the number of stalks with growing tops during the second year of growth. Stalks that flowered and ceased vegetative growth accounted for part of the decline. However, the greater part of the decline was due to stalks that gradually weakened and died-off, possibly due to other factors such as pest and diseases, drought, and lodging etc. Borden (1945 and 1948) observed some primary stalks (millable cane) with dead tops at the 12-month stage and further reported a large number of dead primary stalks in the second year of growth, at the 18-month stage, as a result of flowering. Similarly, in most of the two-year crop cycles (Hawaiian conditions), the significant increase in death of primary stalks between 18 to 24 months of age was a result of lodging and flowering (Van Dillewijn, 1952). In reviewing a number of two year crops, Humbert (1968) reported that mortality of the first season stalks usually ran between 25 and 50%, and he concluded that a number of factors contributed to stalk death including deficiency or excess of moisture, nutrient deficiency, flowering, lodging, rats, insects and diseases.

2.5.2 Effect of crop age on sugar content

There are reports of increased lodging (Rostron, 1972; Pope, 1997) and photorespiration (Bull, 1969) of sugarcane crops with age, which may have indirect effects on stalk sucrose content. Gosnell (1968) reported an increase in sucrose content of cane up to 12 – 15 months, after which it was unaffected by age. Fibre content of cane continued to rise with increasing age. The slow-down in the increase in sucrose content with increased age can be related to reduced light interception and consequently canopy photosynthesis, due to decline in leaf production and LAI with age and probably an increase in respiration losses with age (Inman-Bamber, 1994a). However, it may also be confounded by seasonal factors such as temperature, a major factor affecting canopy development (Inman-Bamber, 1994).

2.6 Concluding remarks

The information presented in this review has highlighted some negative effects of lodging, increasing crop age and varied growth environments such as temperature, radiation interception and soil moisture status on the yield and quality of the harvested cane in different conditions.

However, past studies on sugarcane lodging has been largely descriptive. In most of the lodging studies reviewed, the samples of lodged and erect cane were drawn from different parts of the fields and there could be several other factors such as variability of soil and management conditions, which need to be taken into account during interpretation of the results. No experiments are reported where lodging was specifically prevented.

This review has also demonstrated that sugarcane growth and development are strongly influenced by prevailing environmental (radiation, temperature, nutrient and water availability, and other biotic factors such as diseases/pests) and management factors. Given that there are crops of different size growing at different times of the year, it is difficult to separate the effects of the growth environment, management and crop age, which along with genetic factors, can strongly influence potential yields.

The evidence of spatial variability in sugarcane crop stands and the association of increased crop age and lodging with stalk death had suggested the importance of these factors in determining cane growth and yield. However, the results of the crop growth studies presented in relation to lodging, crop age and seasonal factors were analysed on a unit area basis rather than an individual stalk basis.

Given that, there is a need for further field experimentation to explore the separate effects of lodging on stalk dynamics, cane yield, quality and other parameters, under similar conditions, and using the physiological frameworks presented earlier in this chapter. In particular, a better understanding of the fate of dead stalks and the growth of live stalks in relation to crop age, seasonal factors and lodging would seem vital to successfully address the thesis objectives outlined in Chapter 1.

In the subsequent chapters of this thesis, field experiments are described that were structured to enable the separate effects of lodging, crop age and seasonal conditions on crop growth, biomass and sugar accumulation to be evaluated under controlled conditions. These effects in turn are analysed, using the several physiological frameworks outlined in this chapter, to explore the observed effects not only in terms of growth attributes on a per unit area basis, but also in terms of changes on a per stalk basis and in stalk dynamics. In that way, a clearer understanding is elucidated of the relative importance of lodging, crop age and seasonal effects in causing the slowdown in crop growth, biomass and sugar accumulation that has been observed in well-grown sugarcane crops in northern Australia.

Chapter 3 Field experiments to evaluate alternative causes of the 'yield plateau' in the wet tropics

3.1 Introduction

Field experiments were initiated during 1997/98, in tropical environments of northern Queensland, Australia, to develop a quantitative understanding of the nature and causes of the slowdown in crop growth. Three experimental sites, one in the Burdekin at Ayr and two in the wet tropics (Feluga and Euramo), were established. These field experiments were designed to quantify the separate effects of lodging, crop age and seasonal conditions on crop growth, biomass and sugar accumulation.

Unfortunately, due to an infestation of cane grubs (>3 grubs per stool) in all treatments, the Ayr trial was terminated in April 1998. Of the remaining two sites, lodging was experienced at the Feluga site only.

During 1998/99, two more field experiments, one in the Burdekin and one in the wet tropics, were established to further explore the effects of lodging, crop age and seasonal factors on crop growth and development under irrigated and rainfed conditions.

All the experimental sites had been under sugarcane monoculture for the last 20 to 50 years, having been developed from native woodlands.

In this chapter, details of field experiments are presented for the wet tropical environment only.

3.2 Materials and methods

3.2.1 Location

Three field experiments were conducted under rainfed conditions in the wet tropics near Tully, north Queensland, Australia (Table 3.1).

Table 3.1 Site information for the field experiments designed to evaluate alternative causes of the 'yield plateau' in sugarcane in the wet tropics near Tully.

Experimental site	Longitude	Latitude	Elevation
Feluga (1997/98)	146.0 °E	17.8 °S	10 m
Euramo (1997/98)	145.9 °E	17.9 °S	10 m
Feluga (1998/99)	146.0 °E	17.8 °S	10 m

3.2.2 Treatments

Three treatments were designed to separate the confounding effects of lodging, crop age and seasonal factors (presumably lower temperature, but possibly also lower humidity and/or insolation). For each experiment, these treatments were applied in a randomised block design with a plot size of 12 rows x 40 m and three replicates. The treatments were:

1. Control - normal management. The crops were allowed to lodge naturally.

2. Scaffolding - to prevent lodging. Specially designed bamboo scaffolding, consisting of 6 - 8 rows x 15 - 18 m per plot, was used to prevent lodging (Plates 3.1 and 3.2).

3. Late crop - crop slashed ('ratooned') in December to simulate a late planting and allow a younger crop to grow on after the wet into the winter period.

* In the Euramo (1997/98) experiment, planting was delayed due to wet weather conditions and the scaffolding treatment was not deployed due to the much reduced chance of lodging.

Plate 3.1 One tiered bamboo scaffolding, securing 6 - 8 rows x 15 – 18 m lengths of row per plot, used to prevent lodging in field grown sugarcane at Feluga in 1997/98 and 1998/99. Cross-rails were installed at height of 1.9 – 2.2 m to form a grid of squares with sides of 0.50 - 0.75m to avoid direct pressure on stalks.

Plate 3.2 Two tiered bamboo scaffolding, securing 6 - 8 rows x 18 m lengths of row per plot, used to prevent lodging in field grown sugarcane at Ayr in 1997/98 and 1998/99. Cross-rails were installed at heights of 1.9 and 3.0 m to form a grid of squares with sides of 0.50 - 0.75 m to avoid direct pressure on stalks.

3.2.3 Crop management

In all cases, the crops were grown under maximum or recommended rate of nitrogen fertilisation (Table 3.2).

Table 3.2 Information on cultural operations for the three field experiments designed to evaluate the 'yield plateau' in sugarcane in the wet tropics near Tully.

Experimental site	Variety	Row spacing	Planting date	Fertiliser (kg ha^{-1}) N	P	K	S	Ca
Feluga (1997/98)	Q158	1.65 m	01/06/97	143.8	36.1	66.0	135.9	741.3
Euramo (1997/98)	Q117	1.57 m	29/08/97	217.4	50.4	81.3	22.0	-
Feluga (1998/99)	Q158	1.60 m	25/08/98	297.0	44.8	81.4	319.1	-

Weeds, insects and other pests were controlled as per normal commercial practices (Table 3.3). At Euramo, insecticide 'suSCon Blue' and fungicide 'Shirtan' were applied at planting to control cane grubs and pineapple disease respectively. During 1998/99, at Feluga, fungicide 'Benlate' was applied manually (four times) in pre-marked sample areas to control the 'yellow leaf spot' disease.

Table 3.3 Plant protection measures used on the three field experiments to evaluate the 'yield plateau' in sugarcane in the wet tropics.

Chemical applied	Date of application Feluga (1997/98)	Euramo (1997/98)	Feluga (1998/99)
Herbicide	08/06/97, 14/12/97*	27/02/98, 03/03/98*	25/08/98, 01/12/98, 05/03/99*
Insecticide (suSCon Blue)	-	28/09/97	-
Rodenticide (Klerat wax)	25/03/98, 22/05/98, 04/08/98	03/03/98	05/03/99
Fungicide	-	28/09/97	12/02/99, 5/03/99, 26/03/99, 2/05/99

* - Applied to 'late crop' treatment only

3.2.4 Soil chemical characteristics

Soil samples of 0 - 20cm and 40 - 60 cm layers were taken for comprehensive chemical analysis, from all the experimental sites, at the time of first sample of plant biomass (Table 3.4).

Table 3.4 Results of the soil chemical analyses, conducted for each field site at first sample of plant biomass.

Experimental site	Soil depth (cm)	pH	Electrical conductivity (dS m^{-1})	Organic carbon (%C)	Available N (kg ha^{-1})
Feluga	0 – 20	6.1	0.02	1.1	*
(1997/98)	40 - 60	5.0	0.02	0.5	*
Euramo	0 – 20	5.1	0.04	1.3	*
(1997/98)	40 - 60	4.8	0.04	0.5	*
Feluga	0 – 20	5.7	0.02	1.3	5.9
(1998/99)	40 – 60	4.8	0.02	0.5	4.2

The estimates were done as per standard procedures used by Incitec Ltd.[1].
* - Not measured

3.2.5 Environmental conditions

The climate in the Tully area is hot and humid in summer and mild to cool in winter, with an annual rainfall average of 3500 mm (G. Borgna, personal communication). Consequently, the sugarcane growth period extends from April (when crop growth in the subtropics ceases) to sometimes as late as October/November in the next growth year. The meteorological data were recorded for all three sites with automatic weather stations, which were located about 50 to 500 m from the experimental sites.

3.2.6 Growth measurements

In these experiments, all the future sample areas (quadrats consisted of 2.5 m lengths of the middle four rows) were marked before lodging in the control during January or February. Crop growth analysis was performed using sequential sample harvests of crop biomass taken from the pre-marked sample areas, during January to September, the period in which crop growth slowdown was expected. During 1997/98, both Euramo

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[1] Incitec Ltd., Paringa Road, Gibson Island, Murarrie, Qld 4172

and Feluga sites were sampled at five different times between January 1998 to September 1998 (Table 3.5). During 1998/99, at Feluga, four sequential sample harvests were conducted between January 1999 to September 1999 (Table 3.5).

Table 3.5 Sample harvest dates for the three field experiments evaluating the growth slowdown in sugarcane..

Experimental site	Date of sample harvest				
	1st	2nd	3rd	4th	5th
Feluga (1997/98)	22/01/98	24/03/98	12/05/98	30/06/98	06/09/98
Euramo (1997/98)	22/01/98	23/03/98	11/05/98	02/07/98	02/09/98
Feluga (1998/99)	28/01/99	12/04/99	07/06/99	23/08/99	-

3.2.7 Stalk counts

The initial stalk counts were taken during January or February, after marking the sample quadrats for all the future samplings. Subsequent counts were taken again at each harvest, after harvesting all the plants from a quadrat. Numbers of live, dead, rat-damaged and sucker stalks were recorded as described by Mazzucchelli *et al.* (1997).

3.2.8 Radiation interception

Interception of photosynthetically active radiation (PAR) was measured instantaneously between 1030 h and 1230 h under the green canopy, periodically from the first sampling until final harvest, in the sample areas (or outside the sample areas in the control after lodging). It was measured with an AccuPAR Ceptometer (Decagon Devices, Pullman, USA) and an external quantum sensor (Li-190SA, Li-Cor, Nebraska, USA). These instantaneous PAR interception values were used to estimate daily fractional PAR interception (*fi*). PAR was assumed to amount to one half the energy of solar radiation (Spitters *et al.*, 1986). The amount of radiation intercepted (*Si*) was calculated as the product of the average *fi* between subsequent measurements and the cumulative daily incident radiation (*S*), recorded with a pyranometer (LI-200X, Li-Cor, Nebraska, USA).

3.2.9 Cane yield and biomass partitioning

At each sampling, all plant material from a sample quadrat in each plot was cut at ground level. Load cells (Ruddweigh, Guyra, Australia) were used to determine the total weight (± 0.1 kg) of each sample.

For each sampling, a 16 stalk sub-sample, four from each sample row, was partitioned into green leaves (blades), dead leaves and sheaths, millable stalks and cabbage (immature stalk plus green sheaths) according to the procedures used by Muchow *et al.* (1993) and the 'protocols' given by Mazzucchelli *et al.* (1997). After partitioning, the fresh weights of the components were recorded separately and cane yield was calculated as the product of the quadrat total fresh weight and the proportion of millable cane on fresh weight basis. The millable cane length was measured on each stalk in the sub-sample.

Material from each component was then fibrated using a Jeffco cutter grinder. The fibrated material was mixed thoroughly, and two sub-samples were placed in aluminium foil trays for drying to constant weight at 75°C. After the dry matter content was determined, the biomass per unit land area was determined for each component from their proportion in the total aboveground material on a fresh weight basis and their dry matter content.

The fresh and dry weights of dead and rat-damaged stalks were also recorded.

3.2.10 Commercial cane sugar (CCS) and sugar yield

Sub-samples of fibrated material from millable stalk were taken for juice extraction through a Carver Press (Model M, F. S. Carver Inc., Wabash, Indiana, USA), following the procedures described by Muchow *et al.* (1993). The fresh and dry weight of the remaining biscuit was determined for the calculation of fibre content.

Brix was determined on the juice using an automatic temperature-compensated (20°C) brix meter (Model PR - 1, Atago Pty. Ltd., Tokyo, Japan). For the determination of polarity, 2.5 g of lead acetate was thoroughly mixed with the juice (about 50 ml), the juice was filtered through a Whatman No. 91 filter paper, and the filtrate was passed through a polarimeter (Model AA 5, Optical Activity Ltd., Huntingdon, UK). For determination of CCS, for each class, the following calculations were made:

$$\text{Fibre \% (F)} = ((100 \times DF) - (FF \times B)) / (5 \times (100 - B)) \quad \text{......(i)}$$

$$\text{CCS (\%)} = ((((39 \times P \times (95 - F)) / (99.82) + (0.415 \times B))) - (0.5 \times (B + ((0.00137 - (0.00003 \times B)) \times T^2) + ((0.00172 \times B - 0.0044) \times T) - (0.0224 \times B) - 0.46) \times (97 - F))) / 100 \quad \text{......(ii)}$$

where,

F = fibre percentage;
DF = measured dry weight of biscuit (g);
FF = measured fresh weight of biscuit (g);
P = measured polar in first expressed juice;
B = measured brix in first expressed juice; and
T = temperature of 20°C.

Depending on the amounts of dead and rat-damaged cane, their sugar content was also determined separately. The impact of dead and rat-damaged cane on the final CCS (dilution effects) was calculated as following:

CCS of all stalks (%) = (weight of sound cane × CCS of sound cane + weight of dead or rat-damaged cane × CCS of dead or rat-damaged cane) / (weight of sound cane + weight of dead or rat-damaged cane)......(iii)

Accordingly, the sugar yield was determined for all the treatments at each harvest from the product of fresh millable cane yield and their respective sugar contents.

3.2.11 Other derived measurements

Leaf area index (LAI)

Sub-samples were taken from the green leaves for the determination of specific leaf area (SLA, leaf area per unit leaf weight), in order to calculate leaf area from the total green leaf weight of the sample. The area of leaf blades was determined using a leaf area meter (Delta-T Devices, Cambridge, UK) before drying at 75°C. The LAI was calculated from leaf weight per unit land area and SLA.

Live stalk growth rate

Biomass (total and cane) per live stalk was calculated from the division of the respective stalk biomass by live stalk number. The main purpose was to eliminate any effects of spatial variation in plant populations on estimates of crop growth on a unit area basis and to better understand the stalk growth dynamics in relation to lodging, crop age and seasonal factors (e.g. onset of winter).

Stalk elongation rate

The millable cane length was measured on 16 stalk sub-samples for every plot at each harvest, after partitioning. The relative stalk elongation rate (cm day^{-1}), between successive samplings, was calculated from the increase in length of the millable cane over that time period.

Radiation use efficiency (RUE)

RUE between successive samplings, was estimated from the change in total aboveground biomass and the amount of radiation interception (Si) by the crops during that period.

3.2.12 Data analysis

Statistical analysis of the experimental data was carried out with S-PLUS ver. 2000 (MathSoft Inc., Washington, USA). The analysis of variance (ANOVA) procedures were used for the analysis of the experimental data.

The graphs presented in this chapter were prepared in Microsoft Excel ver. 1997 and S-PLUS ver. 2000 (MathSoft Inc., Washington, USA).

3.3 Results

3.3.1 Crop condition

In all three experiments, there was mild occurrence of leaf rust in the early part of the season (December to March) and 'yellow leaf spot' in the late part of the season (May to July). The incidence of 'yellow leaf spot' was worse in the 1997/98 season and may have reduced the efficiency of leaf photosynthesis and RUE of the crops (Magarey and Croft, 1998). Compared to the late crop treatment, the disease occurrence was more severe in the control and scaffolding treatments.

3.3.2 Occurrence of lodging

Crops were allowed to lodge naturally and very uniform lodging events were experienced except in the Euramo trial, where the control treatment did not lodge at all due to the delayed planting. During the 1997/98 season at Feluga, lodging occurred in May. In this experiment, the late-crop also lodged, in late June. In the 1998/99 season at Feluga, early lodging occurred in February 1999 associated with cyclonic winds, followed by lodging of the top parts of the lodged cane again in April and May. The scaffolding treatment worked very well, during both seasons, to keep the cane erect and to maintain a closed canopy.

3.3.3 Environmental conditions

During 1997/98, the average maximum and minimum temperatures from 'calendar' weeks 15 to 36 (winter months) were 26.8°C and 18.2°C, respectively (Fig. 3.1). These were 2.1°C and 2.5°C higher than the long-term (1961 - 1993) average for the Tully district (Fig. 3.1). Rainfall over the period was lower than average, but came in heavy falls. Solar radiation was periodically low (average 12 – 13 MJ m^{-2} day^{-1}) due to cloud cover (Fig. 3.2).

During 1998/99, the average maximum and minimum temperatures for the winter months (the 'calendar' weeks 15 to 36) were 24.7°C and 16.2°C respectively (Fig. 3.1). These were similar to that of the long term average for Tully district (Fig. 3.1). Rainfall over the period was higher than the long-term average and came in heavy falls (Fig. 3.2). Solar radiation patterns were similar to 1997/98 (Fig. 3.2).

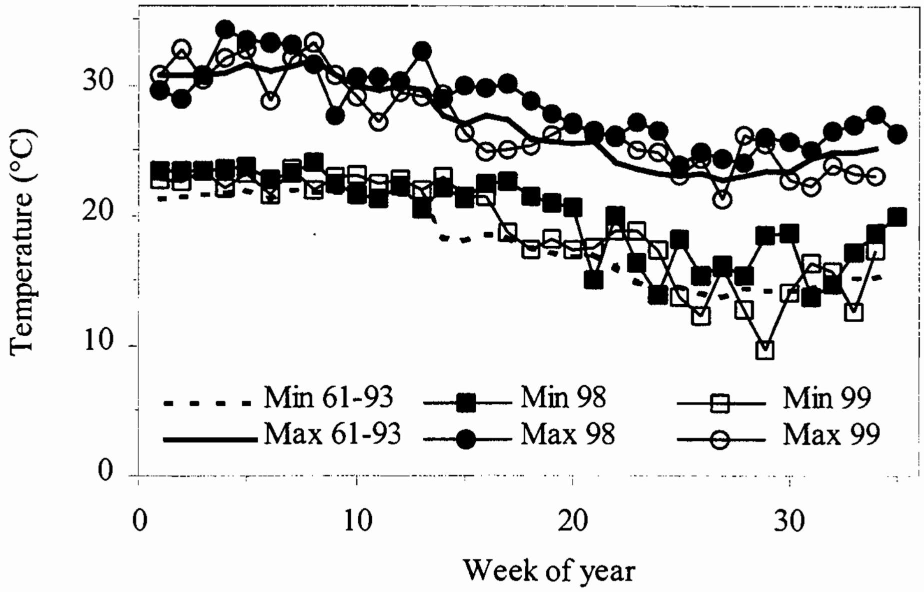

Fig. 3.1 Mean daily minimum and maximum temperature as expressed on a weekly basis for years 1998 (Feluga and Euramo) and 1999 (Feluga) and long-term (1961-93) averages at nearby Tully.

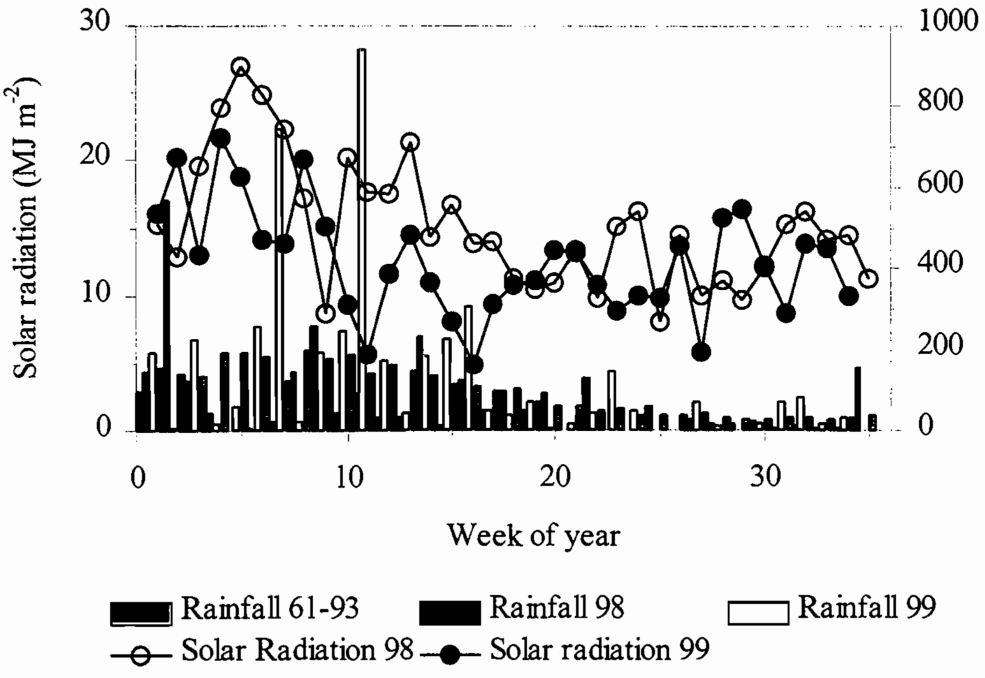

Fig. 3.2 Weekly mean solar radiation and weekly total rainfall during 1998 (Feluga and Euramo) and 1999 (Feluga) and long-term (1961-93) average rainfall at nearby Tully.

3.3.4 Fresh cane yield

Both the scaffolding and late crop treatments followed almost similar trends in fresh cane yield accumulation (Fig. 3.3). However, compared with the scaffolding treatment, a marked decline in rate of cane yield accumulation was observed in the control shortly after lodging at Feluga during both seasons. At the final harvest, the scaffolding treatment produced significantly ($P \leq 0.05$) more (11 – 15%) fresh cane yield than the lodged control. In 1997/98, the occurrence of 'yellow leaf spot' disease (May to June) resulted in a slowdown in cane yield accumulation in both the scaffolding and control treatments.

The cane yield accumulation continued until the final harvest in August/September, except for the control at Feluga (1998/99), where a significant amount of rat-damage was observed in the lodged control (Fig. 3.3).

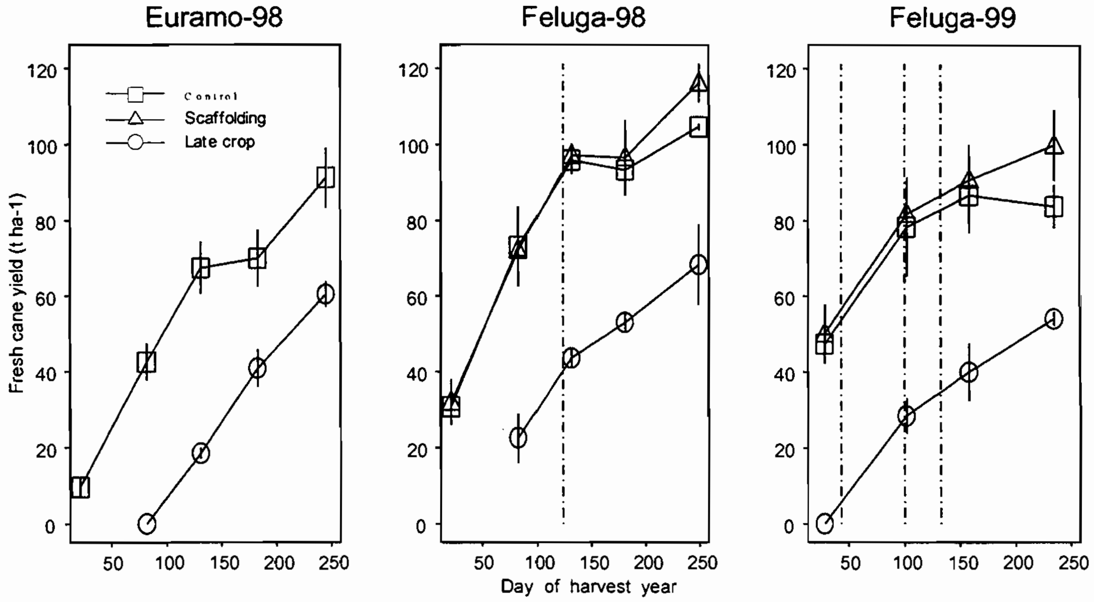

Fig. 3.3 Fresh cane yield accumulation as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

3.3.5 Sugar content and yield

Compared with the scaffolding treatment, the rate of sugar accumulation slowed in the control treatment shortly after lodging at Feluga during both seasons (Fig. 3.4).

However, it recovered later except in the 1998/99 season, where a significant amount of rat-damage was observed only in the control (lodged) treatment.

In 1997/98 at Feluga, during the period between the fourth and fifth samplings, the late crop treatment also experienced lodging, resulting in a reduced rate of sugar accumulation in that period (Fig. 3.4 and 3.5).

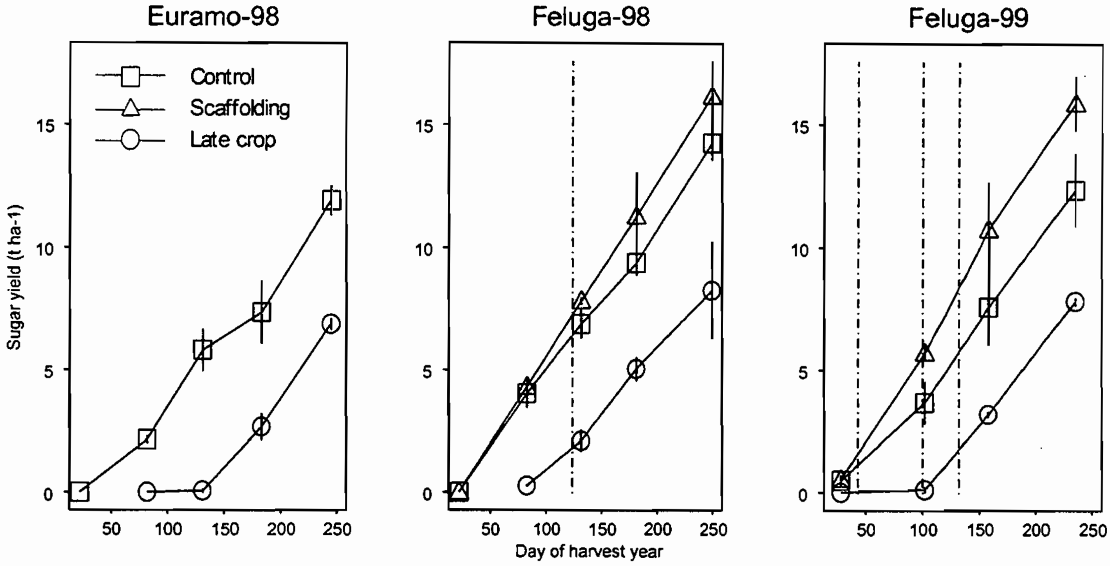

Fig. 3.4 Sugar yield accumulation as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

During 1997/98 at Euramo, a slowdown in the rate of sugar accumulation in the control in the absence of lodging was associated with the occurrence of 'yellow leaf spot' disease. In the Feluga trials, at the samplings conducted after lodging, sugar yield in the scaffolding treatment was significantly higher ($P<0.05$) than that of the control (Fig. 3.4). This was associated with differences in the CCS of live stalks along with the dilution effects from dead and rat-damaged cane (Table 3.6) and differences in cane yield (Fig. 3.3).

During 1997/98 at Feluga, at the final harvest, the CCS of the scaffolding treatment was slightly higher than for the control, but was not statistically significant. However, during

1998/99, the scaffolding treatment produced significantly higher (P<0.05) CCS than the control (Fig. 3.5, Table 3.6).

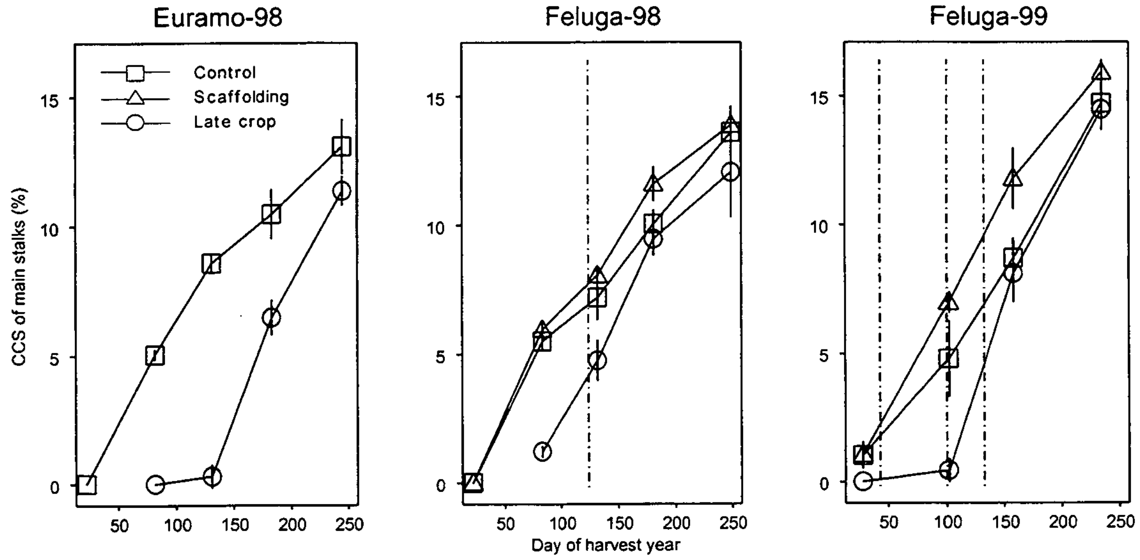

Fig. 3.5 CCS of live stalks as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

Table 3.6 CCS of live stalks as affected by different treatments and the dilution effects of dead and rat-damaged cane. Mean values followed by a common letter are not significantly different at the 5% level.

Site	Date	CCS (%)					
		Live stalks			With dead and rat-damaged cane		
		Control	Scaffolding	Late crop	Control	Scaffolding	Late crop
Euramo (1997/98)	23/03/98	5.03a		*	5.03a		*
	11/05/98	8.57a		0.29b	8.57a		0.29b
	02/07/98	10.47a		6.46b	10.47a		6.46b
	02/09/98	13.09a		11.37b	13.09a		11.37b
Feluga (1997/98)	24/03/98	5.50a	5.95a	1.21b	5.50a	5.95a	1.21b
	12/05/98	7.19a	8.05a	4.75b	7.18a	8.05a	4.75b
	30/06/98	10.04b	11.60a	9.47b	10.00b	11.60a	9.47b
	06/09/98	13.61a	13.88a	12.05a	13.34a	13.88a	11.77b
Feluga (1998/99)	28/01/99	1.03a	1.06a	*	1.03a	1.06a	*
	12/04/99	4.78b	6.98a	0.43c	4.77b	6.98a	0.43b
	07/06/99	8.69b	11.78a	8.10b	8.23b	11.78a	8.10b
	23/08/99	14.71b	15.91a	14.47b	14.00b	15.91a	14.47b

* - Not measured

In all cases, both the control and scaffolding treatments produced higher ($P<0.05$) sugar yield than the late crop at all the samplings due to their high cane yield and high CCS content (Fig. 3.4 and Table 3.6).

3.3.6 Biomass accumulation and partitioning

At all sites, both the scaffolding and late crop treatments followed almost similar trends in the aboveground biomass production (Fig. 3.6). However, compared with the scaffolding treatment, a marked decline in rate of aboveground biomass accumulation was observed in the control shortly after lodging. The accumulation of aboveground biomass continued in all the treatments at all sites until the final harvest in August/September (Fig. 3.6).

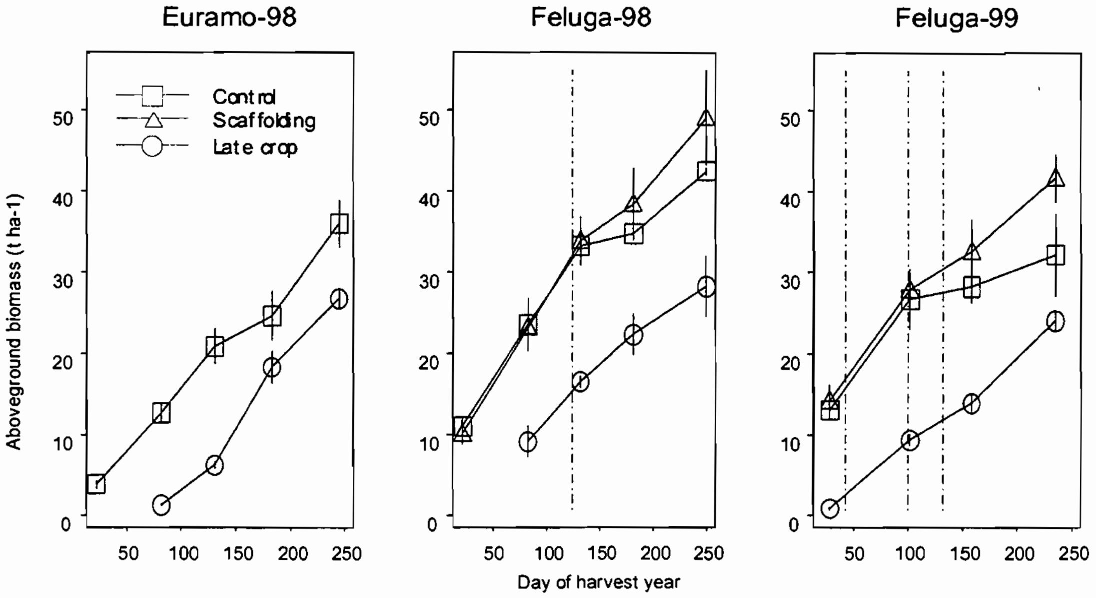

Fig. 3.6 Aboveground biomass accumulation as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

The accumulation of millable cane biomass also followed a similar trend to that of total aboveground biomass accumulation (Fig. 3.7). In all cases, a slight slowdown in the rate of cane biomass accumulation was observed in all the treatments during May - June, a period when the crops suffered from the 'yellow leaf spot' disease.

However, a greater reduction in the rate of cane biomass accumulation was observed in the control after lodging as compared to the scaffolding and late crop treatments in both years at Feluga. Most interestingly, none of the treatments experienced plateau in cane biomass accumulation (Fig. 3.7).

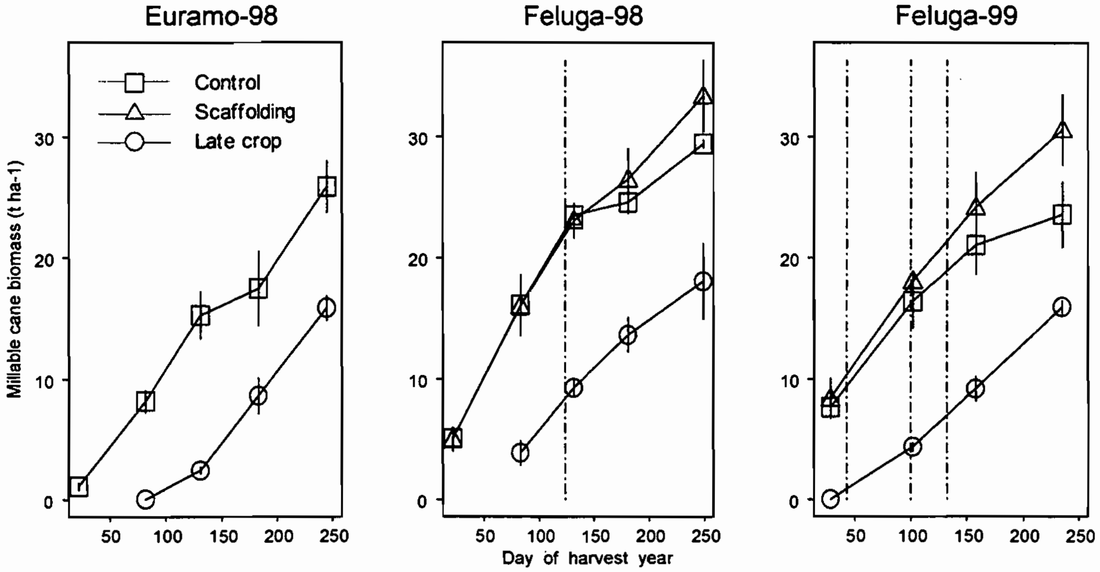

Fig. 3.7 Cane biomass accumulation as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

The accumulation of green leaf biomass declined with time in the three treatments at all sites (Fig. 3.8). In both years at Feluga, a higher rate of decline was observed in the control treatment compared to the scaffolding treatment.

The occurrence of 'yellow leaf spot' disease contributed to reductions in green leaf biomass in all the treatments between May and June in both seasons. The disease effect was more severe during 1997/98 and an increase in accumulation of green leaf biomass was observed (all treatments) towards the end of season (Fig. 3.8), when the disease had subsided.

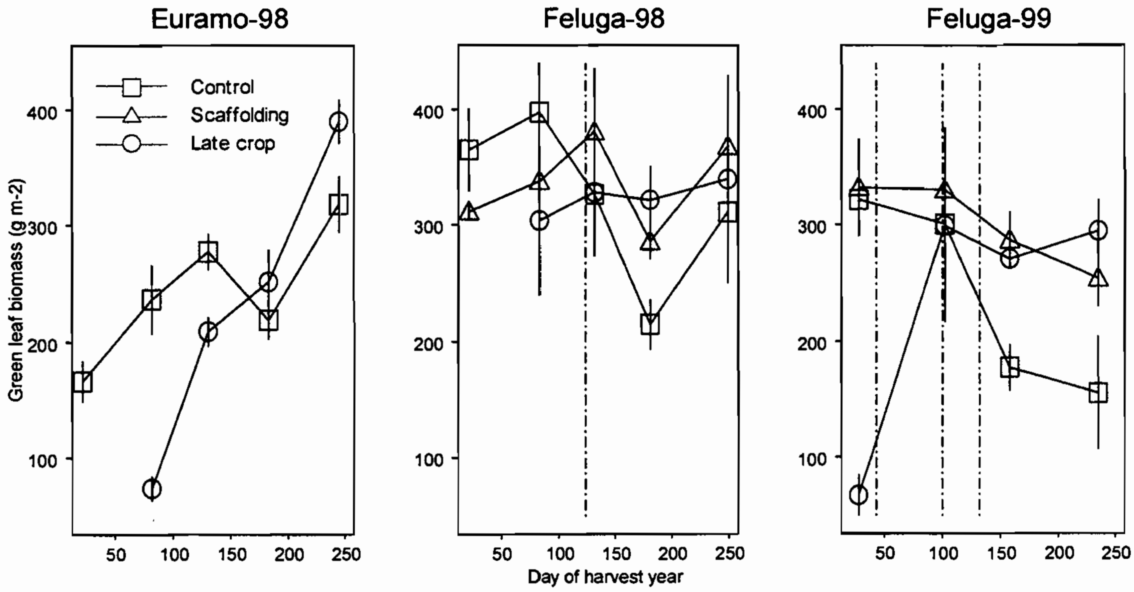

Fig. 3.8 Green leaf biomass production as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

The pattern of accumulation of cabbage biomass (Fig. 3.9) was almost identical to that for green leaf biomass, whereas there was an increase in the accumulation of the trash biomass over time in all the treatments (Fig. 3.10).

At the final harvest, at all sites, the three components (green leaf, cabbage and trash) together comprised 26 - 31% of the total above ground biomass in the scaffolding and control treatments compared with 33 - 40% in the late crop treatment (Fig. 3.11 and 3.12). Earlier in the growth period, these three components comprised a larger proportion of the total aboveground biomass but as biomass increased, the fraction as millable stalk increased exponentially while the fraction as green leaf and cabbage declined (Fig. 3.11 and 3.12).

There was no consistent effect of lodging on the partitioning of biomass among the components of millable stalk, green leaf, cabbage and trash, all the treatments showing a broadly similar relationship (Fig. 3.11 and 3.12).

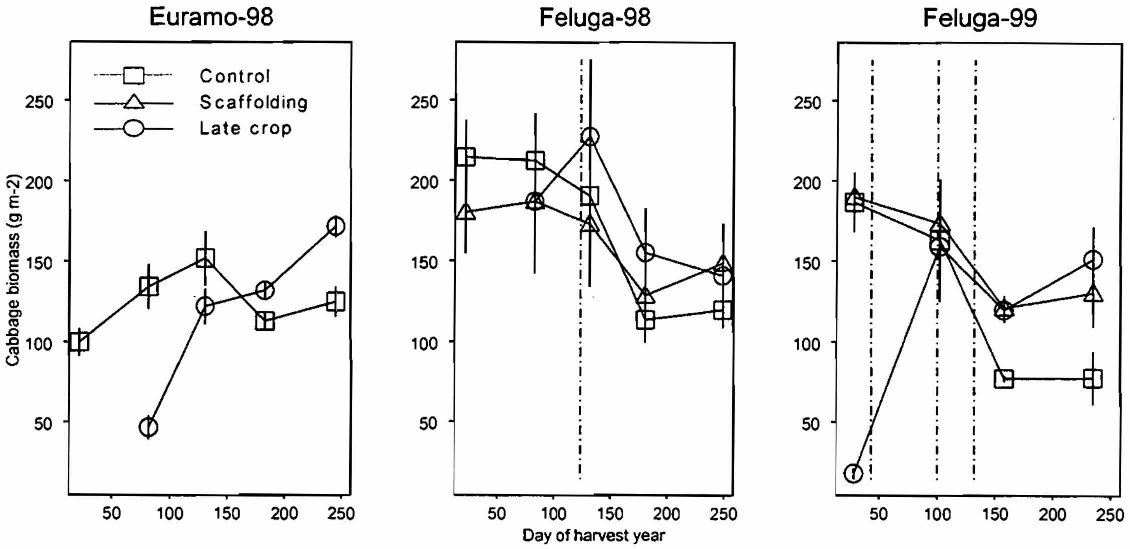

Fig. 3.9 Cabbage biomass production as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

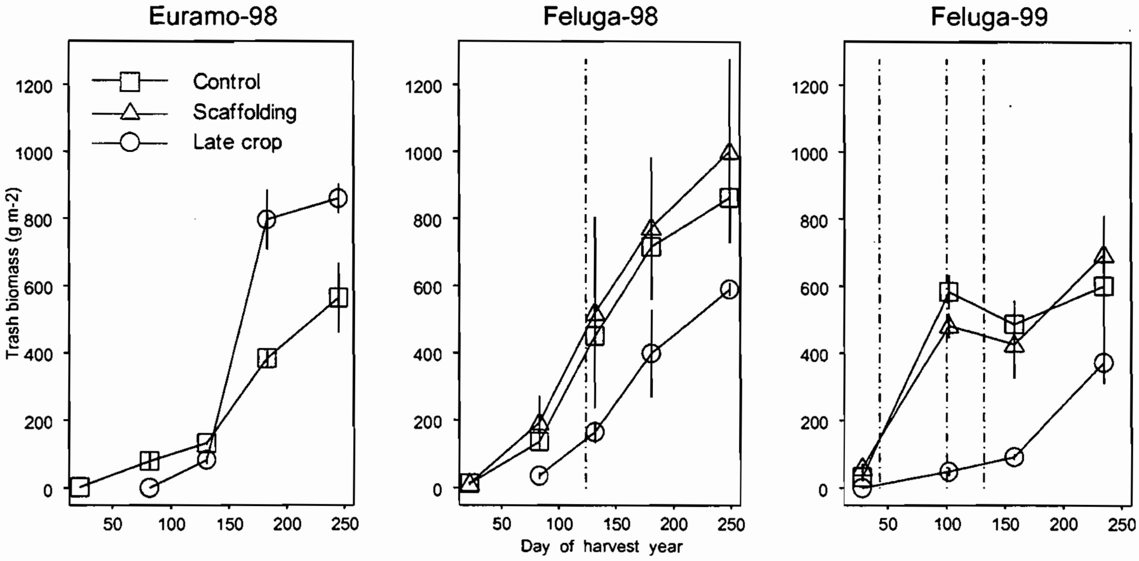

Fig. 3.10 Trash biomass production as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

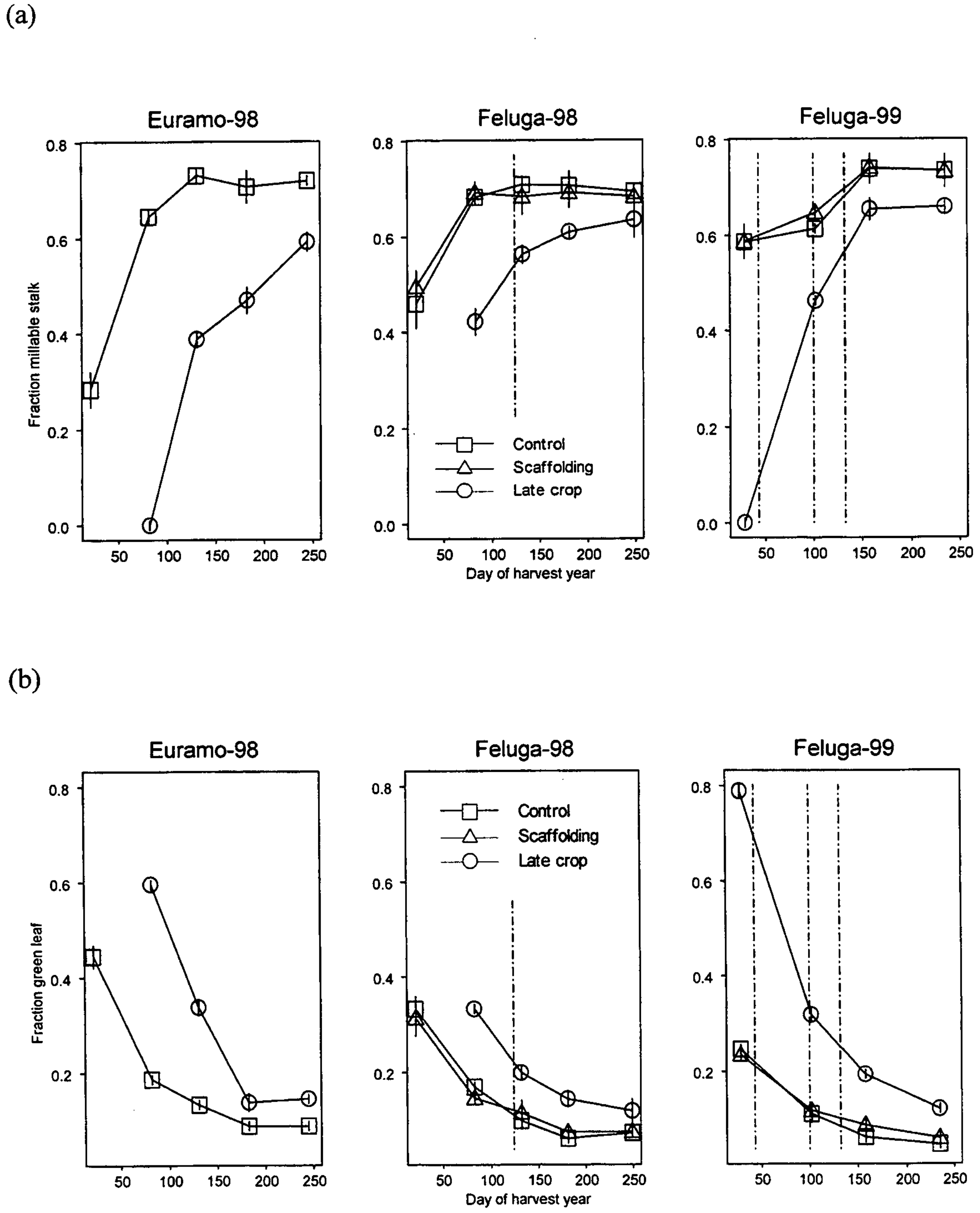

Fig. 3.11 Fraction of biomass as (a) millable stalk and (b) green leaf as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

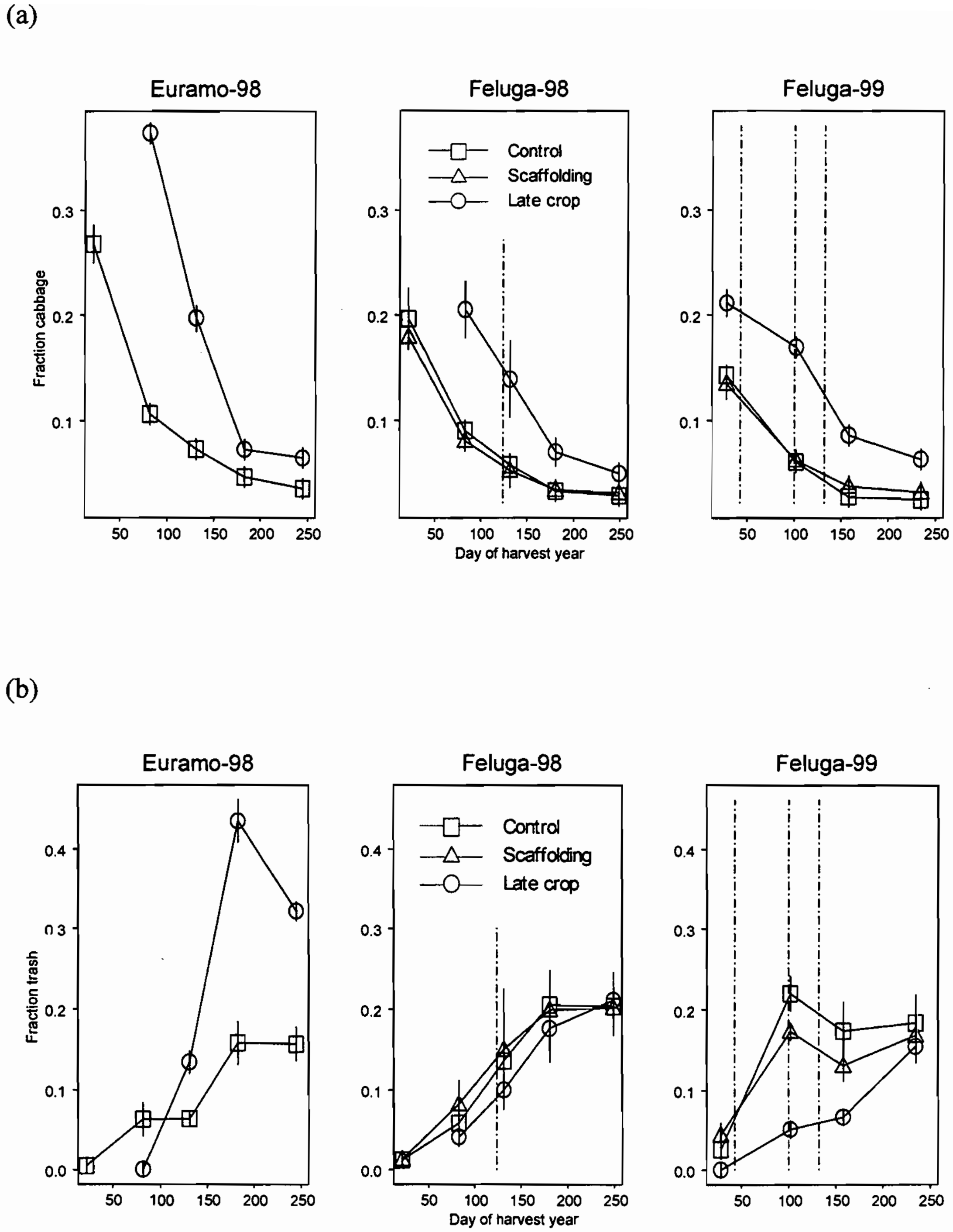

Fig. 3.12 Fraction of biomass as (a) cabbage and (b) trash as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

Compared with the scaffolding and late crop treatments, there was a significant amount of dead cane biomass in the control after lodging at Feluga in both seasons (Table 3.7).

Table 3.7 Dead cane biomass accumulation under different treatments at Feluga. Mean values followed by a common letter are not significantly different at the 5% level.

Site	Date	Dead cane biomass ($g\ m^{-2}$)		
		Control	Scaffolding	Late crop
Feluga (1997/98)	12/05/98	0.0a	0.0a	0.0a
	30/06/98	25.5a	0.0b	0.0b
	06/09/98	36.8a	0.0b	46.7a
Feluga (1998/99)	28/01/99	0.0a	0.0a	0.0a
	12/04/99	21.0a	0.0b	0.0b
	07/06/99	175.6a	0.0b	0.0b
	23/08/99	114.5a	0.0b	0.0b

3.3.7 Stalk dynamics

Stalk number

At Feluga, in both 1997/98 and 1998/99, the scaffolding and control treatments had similar numbers (about 8 stalk m^{-2}) of stalks at the start of the experiments (Fig. 3.13).

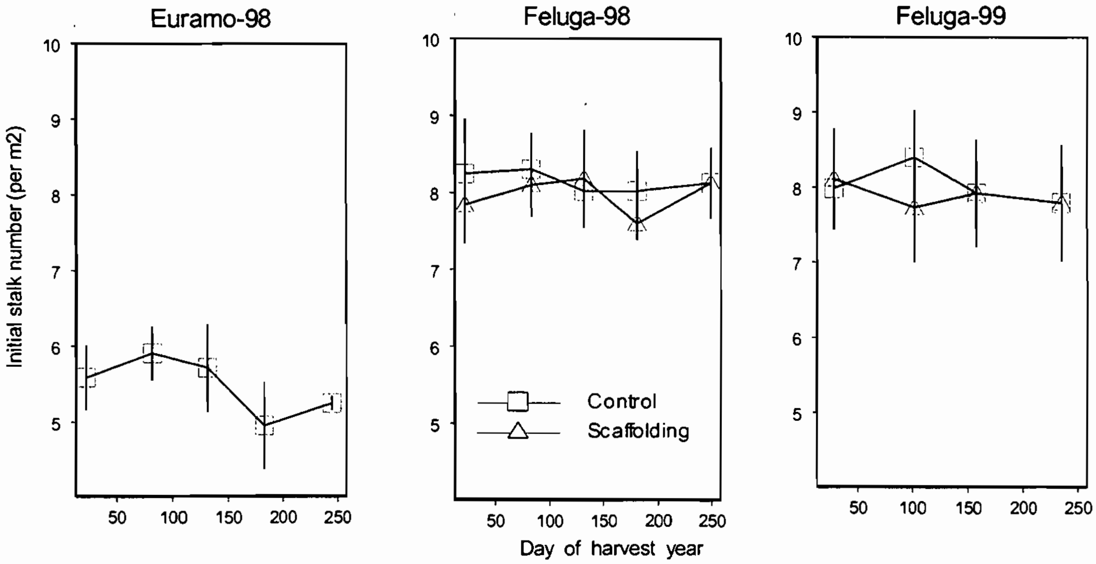

Fig. 3.13 Stalk numbers recorded at the start of the experiments for areas designated to be sampled at different times in the control and scaffolding treatments. Bars represent ± SE of the means.

In the case of the Euramo trial, the initial stalk numbers were very low (<6 stalks m^{-2}) and quite variable across the samplings because planting had been under very wet conditions.

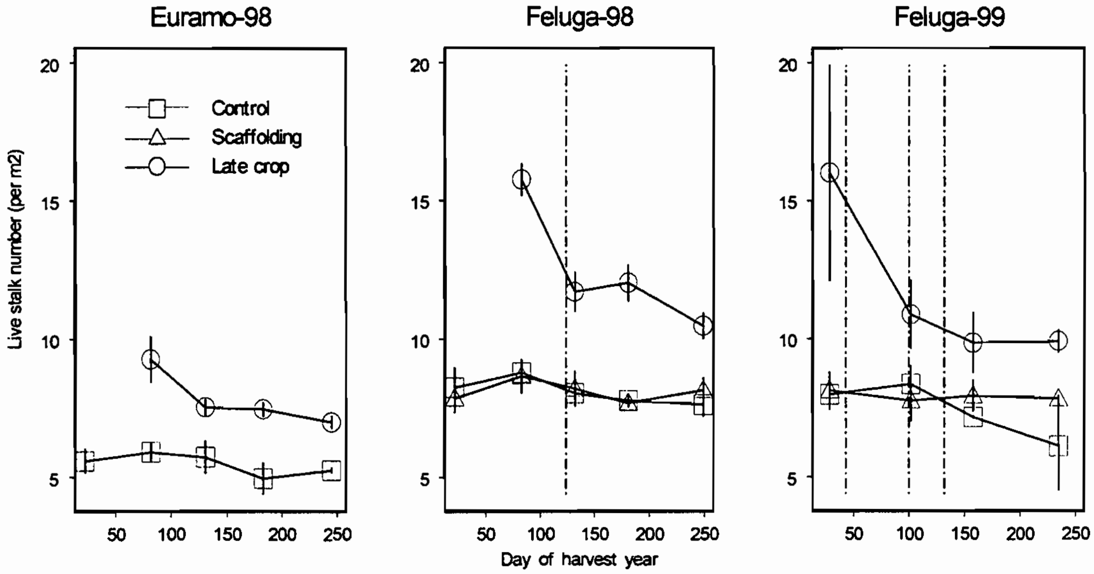

Fig. 3.14 Live stalk number recorded at each harvest in different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and the dotted lines show the date of lodging in the control treatment.

No differences were observed in the final stalk numbers between the scaffolding and control treatments at any harvest during 1997/98 at Feluga (Fig. 3.14, Table 3.8). However, a reduction in the number of live stalks was observed in the control treatment at the August samplings at Feluga during 1998/99 (Fig. 3.14, Table 3.8).

Compared with the scaffolding treatment, there was a greater ($P \leq 0.05$) number of dead stalks in the control after lodging due to stalk breakage/smothering (Table 3.8). However, there was no net loss, i.e., no complete disappearance of the stalks, with all the stalks recorded in the quadrats before lodging accounted for. At Feluga in 1998/99, a significant amount of rat-damage (0.9 stalk m^{-2}) was recorded in the control treatment.

At all sites, in the late crop treatment, there was reduction in stalk number after the first harvest with final numbers stabilised at two stalks (m^{-2}) greater than in the scaffolding or control treatments.

Table 3.8 Live (initial and final) and dead stalk number (for Control, C; scaffolded, S; and late crop, LC treatments) at Feluga during 1997/98 and 1998/99. Mean values followed by a common letter are not significantly different at the 5% level.

Site	Date	Stalk number (per m^2)							
		Initial		Final			Dead		
		C	S	C	S	LC	C	S	LC
Feluga (1997/98)	22/01/98	8.2a	7.8b	8.2a	7.8b	*	0.0a	0.0a	0.0a
	24/03/98	8.3a	8.1a	8.8b	8.6b	15.7a	0.0a	0.0a	0.0a
	12/05/98	8.0a	8.2a	8.0b	8.2b	11.7a	0.0a	0.0a	0.0a
	30/06/98	8.0a	7.6a	7.8b	7.7b	12.0a	0.3a	0.0b	0.0b
	06/09/98	8.1a	8.1a	7.6b	8.1b	10.4a	0.6a	0.0b	0.8a
Feluga (1998/99)	28/01/99	8.0a	8.1a	8.0b	8.1b	16.0a	0.0a	0.0a	0.0a
	12/04/99	8.4a	7.7a	8.3b	7.7b	9.8a	0.1a	0.0b	0.0b
	07/06/99	8.2a	7.9a	7.2b	7.9b	9.8a	1.0a	0.0b	0.0b
	23/08/99	7.8a	7.8a	7.0c	7.8b	9.9a	0.8a	0.0b	0.0b

* - Not measured

At Feluga in both seasons, a small number (<1.5 m^{-2}) of suckers was recorded towards the end of the season (Fig. 3.15). The sucker biomass was negligible in all the treatments at all sites (Fig. 3.16). There was no consistent effect of lodging on sucker number or on sucker biomass production, with all the treatments showing a similar relationship (Fig. 3.15 and 3.16).

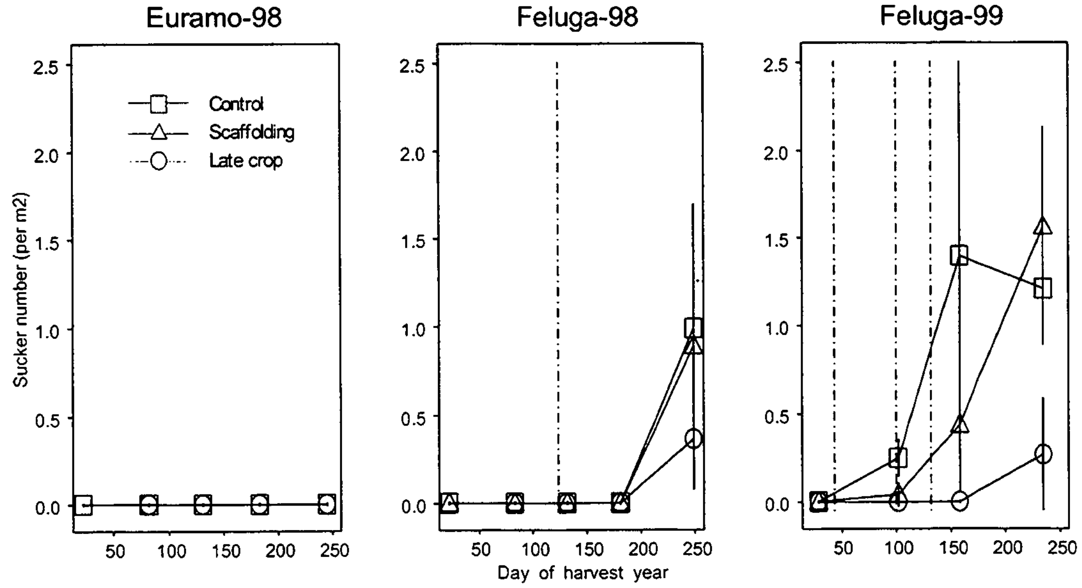

Fig. 3.15 Sucker number recorded at each harvest in different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and the dotted lines show the date of lodging in the control treatment.

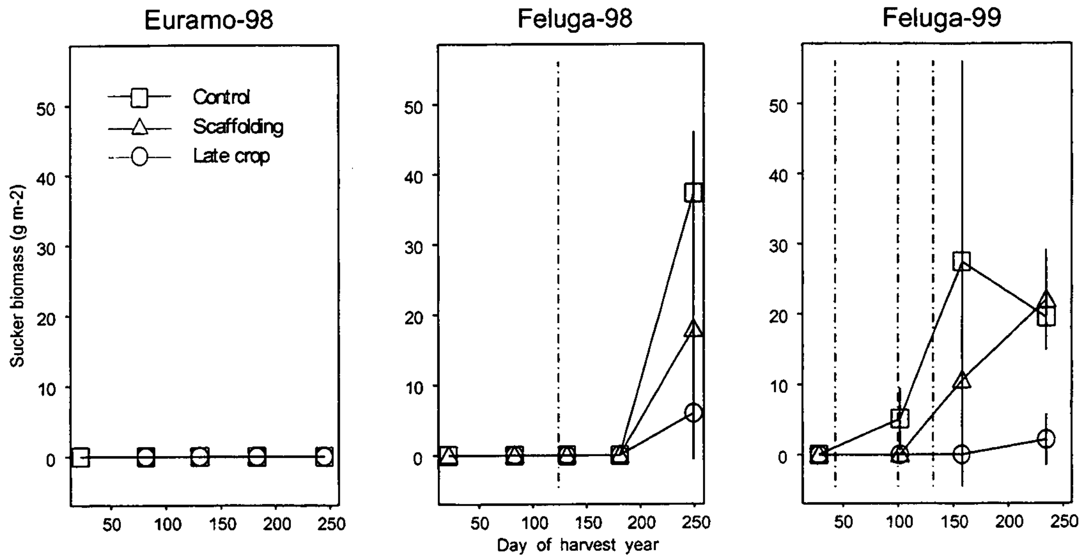

Fig. 3.16 Sucker biomass recorded at each harvest in different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and the dotted lines show the date of lodging in the control treatment.

Individual stalk growth

There was a significant linear increase in aboveground biomass per live stalk over time, from the first harvest to the final harvest, in all the treatments at all sites (Fig. 3.17). Similarly, millable cane biomass per live stalk also increased significantly over time in all the treatments at all sites (Fig. 3.18).

However, the variations in the slopes of the relationships of individual stalk biomass (total and millable cane) over time among different treatments reflect the fact that the relative rates of stalk biomass accumulation changed over time. Relative stalk growth rate declined towards the end of the season in all the treatments at all sites (Fig. 3.17 and Fig. 3.18). But compared with the scaffolding treatment, there was a greater rate of decline in the control after lodging at Feluga (1997/98 and 1998/99).

At the sampling conducted after lodging in the control, the scaffolding treatment produced significantly ($P<0.05$) more cane weight per live stalk than the control treatment at Feluga during both seasons (Fig. 3.18). However, during 1998/99, this effect of lodging on cane weight of live stalks was sustained until the final sampling (Fig. 3.18).

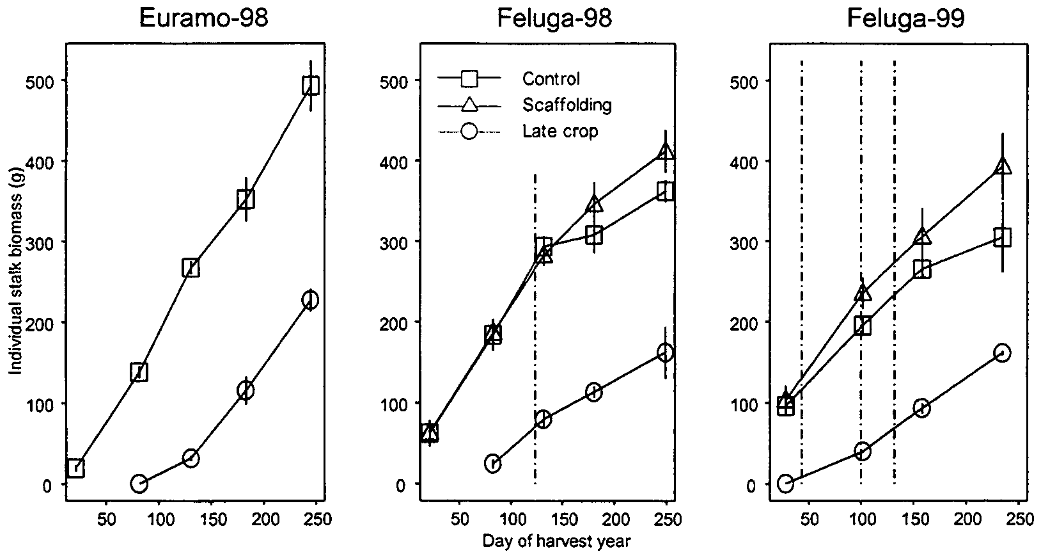

Fig. 3.17 Total biomass per live stalk as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

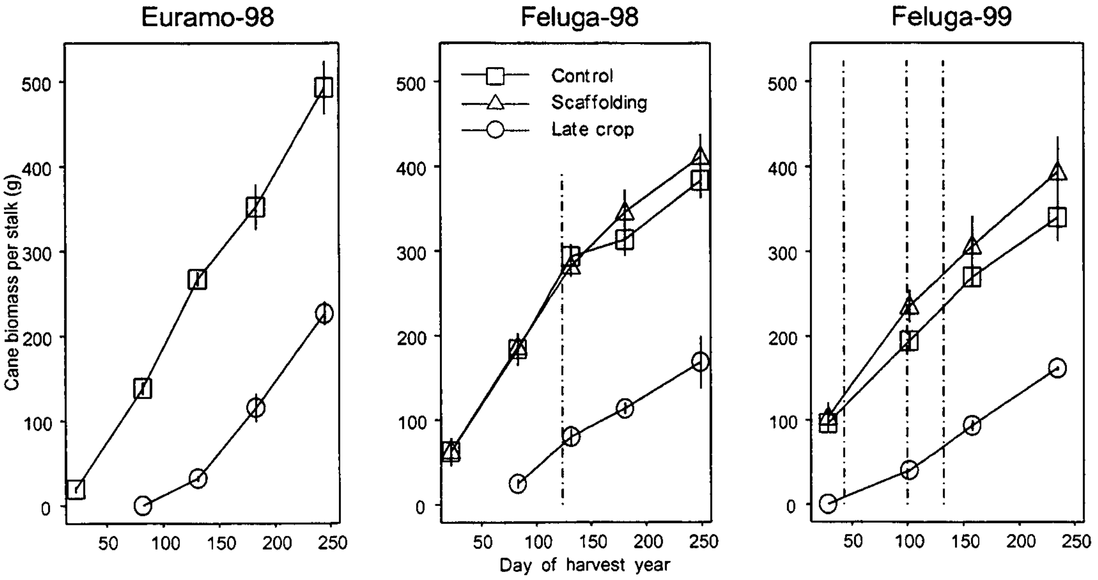

Fig. 3.18 Cane biomass per live stalk as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

Stalk elongation rate

Stalk elongation, in all treatments, was curvilinear over time at all sites (Fig. 3.19). At Feluga (1997/98 and 1998/99), no differences were observed in millable cane length between the scaffolding and control treatments, except for the samplings conducted after lodging in the control, when the length of millable cane was significantly higher ($P<0.05$) in the scaffolding treatment. The maximum rate of stalk elongation (cm day^{-1}) was observed during the period between January (1st sample harvest) to March/April (2nd sample harvest) in all three treatments and then declined later in the season irrespective of crop age.

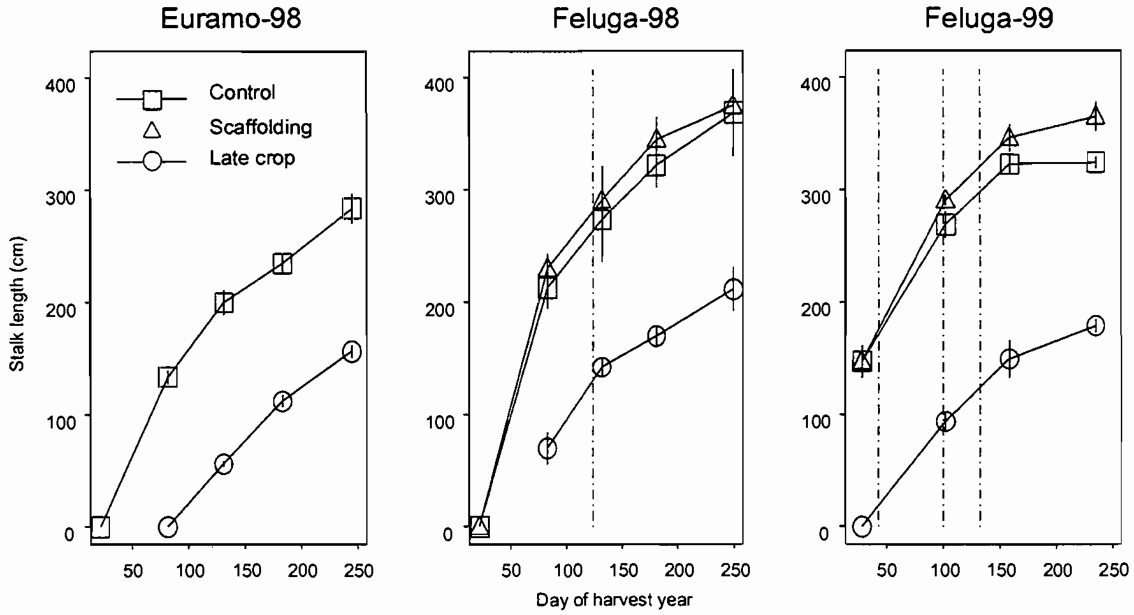

Fig. 3.19 Millable cane length as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

3.3.8 Leaf area index (LAI)

At Feluga in 1997/98, no differences were observed in LAI of the crops except for the 4th (June) harvest when it was lower in the control than the late crop. LAI was lower in all the treatments in June and increased again towards the end of the season (Fig. 3.20).

At Euramo, the control treatment produced higher LAI than the late crop until the 3rd (May) harvest. However, at the final harvest in September, there was a higher LAI in the late crop than the control. In the case of Feluga in 1998/99, no differences were observed in LAI between the control and scaffolding treatments at the first two harvests. In all treatments, the maximum value of LAI was observed at the April (2nd) harvest and then declined over time until the final harvest. However, compared to the scaffolding and late crop treatments, there was a greater rate of reduction in LAI in the control after lodging (Fig. 3.20).

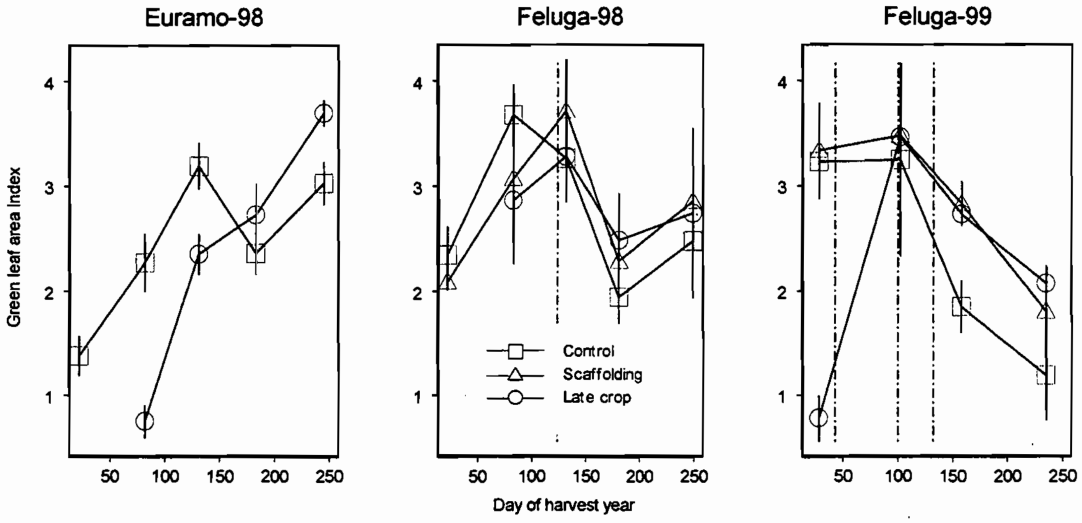

Fig. 3.20 Leaf area index (LAI) as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

3.3.1 Radiation interception and radiation use efficiency (RUE)

At the first harvest, the measured *fi* was similar for both the control and scaffolding treatments in both Feluga experiments (Fig. 3.21). The values were 0.80 and 0.75 for the 1997/98 and 1998/99 seasons, respectively. The *fi* of the scaffolding and control treatments changed little until late April but then declined slightly, in all treatments, in line with reductions in LAI of the crops due to increased leaf senescence. However, a greater rate of decline in radiation interception was observed in the control treatment after lodging during both seasons (Fig. 3.21). In contrast, at both locations, the *fi* of the late crop treatment increased over time from the first harvest until April and then declined slowly towards the end of season (Fig. 3.21).

In the case of the Euramo experiment, both the control and the late crop treatment followed similar trends in radiation interception. In the control treatment, a reduction in *fi* was observed late in the season due to reductions in LAI of the crops. At the final harvest in September, *fi* values of 0.69 and 0.76 were recorded for the control and late crop treatments respectively.

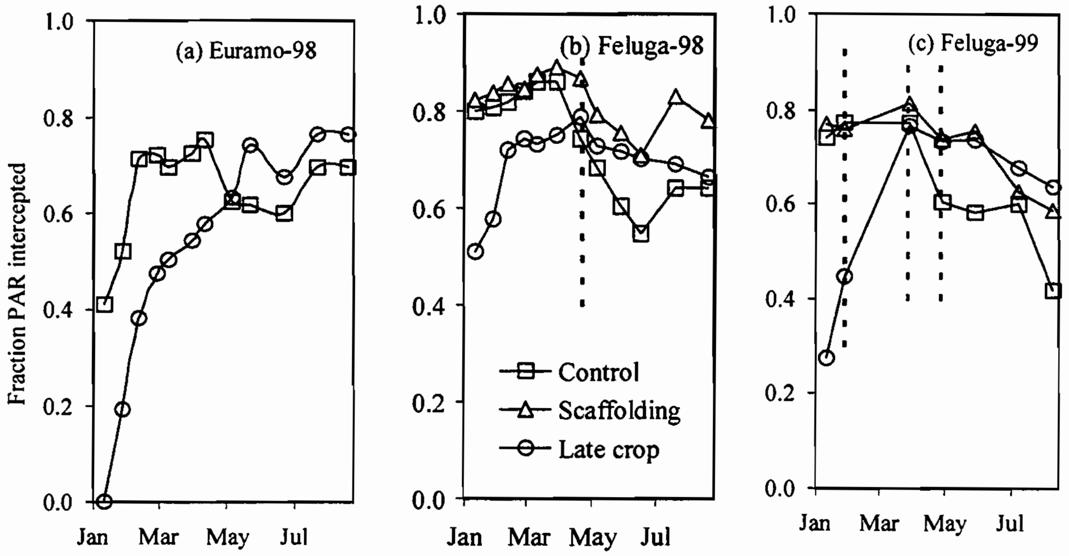

Fig. 3.21 Fraction of PAR interception at (a) Euramo-98, (b) Feluga-98 and (c) Feluga-99, as affected by different treatments, with time from the first sample harvest. Dotted lines show the date of lodging in the control treatment.

The relationship between aboveground biomass accumulation and *Si* was linear for the scaffolding and late crop treatments at Feluga during both seasons (Fig. 3.22). Compared to the scaffolding and late crop treatments, the poor relationship in the control was probably due to the shading effects as a result of clumping of the stalks/leaves and overlapping of the green leaves after lodging, an effect that is difficult to sample effectively.

At Feluga in 1997/98, for the period between the first and second samplings, the calculated radiation use efficiency (RUE; given by the slope of the line) values were 1.45, 1.50 and 1.34 g MJ^{-1} m^{-2} for the control, scaffolding and late crop treatments respectively (Fig. 3.23). The RUE increased in all the treatments from the second to third harvest (March to May) in the order of scaffolding>lodging>late crop treatment.

The RUE of the control and scaffolding treatments declined from the third to fourth harvest, a period when the crops suffered from 'yellow leaf spot' disease and then increased between the fourth and fifth harvests (Fig. 3.23). However, in the case of the late crop, maximum RUE was recorded between the third and fourth harvests and then declined from the fourth to fifth harvests when this treatment also experienced lodging.

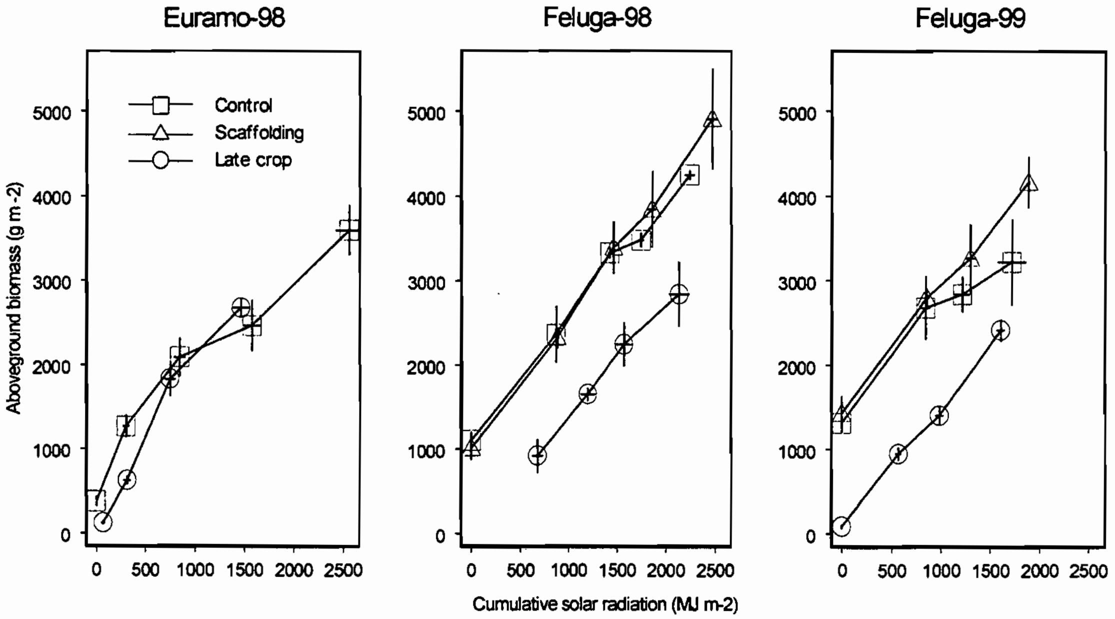

Fig. 3.22 The relationship between aboveground biomass accumulation and solar radiation intercepted, from the first sample harvest, as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

During 1998/99 at Feluga, between the first and second sample harvests, the average RUE was 1.69, 1.56 and 1.51 g MJ^{-1} m^{-2} for the control, scaffolding and late crop treatments respectively. A reduction in the RUE of all treatments was observed for the period between the second and third samplings (Fig. 3.23). However, a higher rate of decline was recorded in the control treatment, which was sustained until the last harvest. In contrast, an increase in RUE of the scaffolding and late crop treatments was observed between the third and fourth samplings.

Similarly, at Euramo, the RUE of the control treatment declined between the third and fourth samplings (May to June) and then increased from the fourth to fifth samplings.

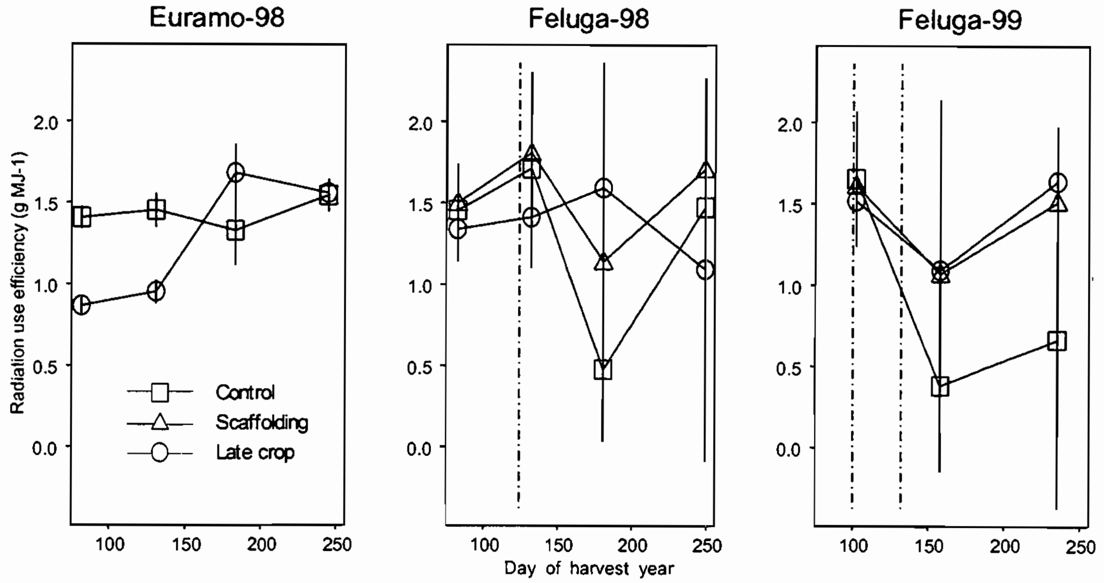

Fig. 3.23 Radiation use efficiency (RUE) of the crops as affected by different treatments designed to establish the cause of the 'yield plateau'. Bars represent ± SE of the means and dotted lines show the date of lodging in the control treatment.

3.3.10 Summary of results for the wet tropics trials

The key findings from these studies are that lodging had a significant negative impact on crop growth, sucrose accumulation, and cane and sugar yield. Lodging affected a number of growth and yield attributes such as live stalk number, live stalk CCS, LAI, RUE, stalk length and live stalk biomass (total and millable cane) accumulation. In addition, a significant amount of rat-damage was also observed at Feluga in 1998/99, in the control treatment only after lodging. The growth rates of the late crop at all the sites, and of the control at Euramo, where this treatment did not lodge at all, were similar to those of the non-lodged crops.

Lodging reduced both the sugar concentration (by 4 – 14%) and fresh cane yield (by 3 – 10%), and increased the susceptibility of the crops to pest infestations. The effects of lodging on CCS were greatest immediately after lodging, while effects on cane yield were present and sustained throughout the growth periods after lodging at Feluga during 1997/98. All these factors in combination resulted in about 14% reduction in sugar yield in the control compared to the scaffolding treatment at the final harvest in September 1998. However, during 1998/99 at Feluga, lodging had a continuous and large impact on stalk CCS and cane yield leading up to the final harvest in August 1999. The reduction in sugar yield was much higher (26%) under the lodged control, and was associated with the greater intensity and frequency of lodging events and extent of rat-damage. These results are similar to those of an artificial lodging experiment reported by Vaidyanathan (1954), where a sugar yield reduction of 16 to 25% was observed from lodging.

The yield reductions under lodging were mainly the result of lower sugar content (2 – 8%) and lower cane biomass (7 – 16%) of the live stalks and a reduction (up to 13%) in the number of live stalks. There were also additional dilution effects from the low sugar concentration of the dead and rat-damaged cane, which was about 5.0 to 6.5 units lower than the mean CCS of all cane. Compared with the scaffolding treatment, and depending on the nature and extent of lodging and the occurrence of rat-damage, significant amounts of dead (6 – 13%) and rat-damaged (12%) cane were recorded in the control after lodging.

The lower stalk biomass following lodging was also related to reductions (up to 10%, compared with the scaffolding treatment) in radiation interception as a result of disruption of crop canopies and a decrease in LAI from increased leaf senescence. Lodging also reduced the RUE of the crops, due partly perhaps to mutual shading because of clumping of stalks or leaves after lodging and to stalk death. There are reports on reductions in crop growth rate in cereals as a result of less-favourable distribution of light amongst leaves following lodging (Van Dobben, 1966; Hanson *et al.*, 1985).

Although there was a slowdown in the rate of cane biomass accumulation in the control after lodging in both Feluga experiments, it was not as large as that observed by Muchow *et al.* (1995). However, none of the treatments experienced a plateau in biomass or sugar yield accumulation and there was no net loss of stalk numbers as observed in the Muchow *et al.* (1995) studies, even under early lodging conditions at Feluga during 1998/99. One of the possible reasons for the absence of a 'plateau' in these trials may be the difference in type or intensity of lodging as compared to the Muchow *et al.* (1995) studies, where the accumulation of biomass and sugar yield had ceased at 300 days after planting or ratooning.

Chapter 4 Field experiments to evaluate alternative causes of the 'yield plateau' in the dry tropics

4.1 Introduction

As noted previously, two field experiments were conducted under irrigated conditions at Ayr (147.3 °E, 19.4 °S) in north Queensland, Australia in 1997/98 and 1998/99, to explore the causal factors of the 'yield plateau' under dry tropical conditions (Table 4.1). The same three treatments were imposed in these experiments as were imposed in the wet tropic sites at Feluga and Euramo. Unfortunately, the first field trial at Ayr in 1997/98 had to be abandoned at an advanced stage after an epidemic infestation of cane grub devastated all treatments at that site. Prior to its abandonment, however, the first Ayr experiment provided evidence that the scaffolding treatment was able to prevent lodging in very heavy irrigated cane crops, under a situation where extensive natural lodging occurred in its absence (Plate 4.1). Thus, despite its failure in terms of the original objectives, the first experiment at Ayr demonstrated that it was possible to test the treatments in that location provided steps were taken to control cane grubs.

The second experiment conducted under irrigated conditions at Ayr during 1998/99 was laid out in a randomised design with three treatments (control, scaffolding and late crop) similar to the Feluga experiments discussed earlier. The details of this experiment are given below.

4.2 Materials and methods

4.2.1 Crop management

In 1998/99, variety Q117 was planted on 18 April 1998 at a row spacing of 1.50 m (Table 4.1). Fertiliser, 'Grow Force – 352' (11.5% N, 3.2% P, 20.8% K and 10.5% S; @ 376 kg ha^{-1}), was applied at planting and as side dressings on 25 August 1998 (as ammonium sulphate, 20.2% N and 24% S, @ 659kg ha^{-1} and as elemental sulphur @ 220 kg ha^{-1}). In January 1999, ammonium sulphate was applied again manually @ 530 kg ha^{-1}.

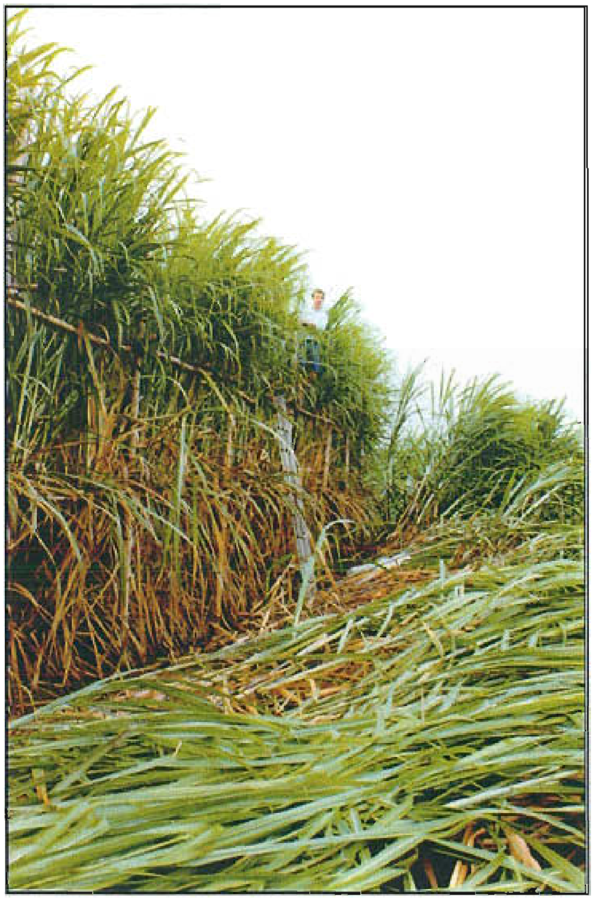

Plate 4.1 Bamboo scaffolding holding sugarcane crop upright with lodged crop in the foreground in a field experiment at Ayr in 1997/98. This trial was abandoned at an advanced stage in April 1998, after all the treatments were devastated by an epidemic infestation of cane grubs.

In the second experiment at Ayr during 1998/99, extra precautions were taken against the cane grubs. Insecticide 'suSCon Blue' was applied on 25 August 1998 @ 24.7 kg ha^{-1}, with ammonium sulphate, directly to the soil. Fertilisers, ammonium sulphate and elemental sulphur were used to acidify the soil to improve the effectiveness of grub control with insecticide 'suSCon Blue'. The beetles were also controlled with two aerial applications (5th and 11th November 1998) of insecticide 'Carbaryl' @ 1 kg ha^{-1}. Weeds were controlled as per normal commercial practice (Table 4.2).

Table 4.1 Information on cultural operations for the field experiments at Ayr designed to evaluate the 'yield plateau' in sugarcane.

Site	Variety	Row spacing	Planting date	Irrigation	Fertiliser (kg ha^{-1}) N	P	K	S
Ayr (1997/98)*	Q96	1.50 m	21/04/97	Furrow	216	19	71	12
Ayr (1998/99)	Q117	1.50 m	18/04/98	Furrow	285	12	78	545

* - Abandoned in April 1998 due to infestation of cane grubs (>3 grubs per stool).

Table 4.2 Weed control measures used on the field experiment at Ayr to evaluate the 'yield plateau' in sugarcane in 1998/99.

Date of application	Herbicide applied
21/05/1998	Atrazine + Gramoxone + 2,4 D
08/01/1999	Atrazine + Gramoxone + 2,4 D
08/03/1999	Diuron*
10/03/1999	2,4 D*

* - Late crop treatment only

4.2.2 Soil chemical characteristics

Soil samples of 0 – 20 cm and 40 - 60 cm layers were taken for comprehensive chemical analysis, at the time of first sample harvest. The estimates were done as per standard procedures used by Incitec Ltd.[1] (Table 4.3).

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[1] Incitec Ltd., Paringa Road, Gibson Island, Murarrie, Qld 4172

Table 4.3 Results of the soil chemical analysis conducted at first harvest at the Ayr site in 1998/99.

Soil depth (cm)	pH	Electrical conductivity (dS m^{-1})	Organic carbon (%C)	Available N (kg ha^{-1})
0 – 20	6.8	0.07	1.4	28.6
40 - 60	6.4	0.17	1.5	50.9

4.2.3 Irrigation management

The crop was furrow irrigated and detailed information on irrigation is given in Table 4.4. The irrigation interval was lengthened later in the season before the second last harvest. There was a drying-off period of about seven weeks before the final harvest.

Table 4.4 Information on irrigation applications for the field experiment at Ayr designed to evaluate the 'yield plateau' in sugarcane.

Irrigation Number	Date of application	
	Control/Scaffolding	Late crop
1.	25/04/1998	-
2.	09/08/1998	-
3.	01/10/1998	-
4.	13/10/1998	-
5.	30/12/1998	30/12/1998
6.	25/01/1999	25/01/1999
7.	08/02/1999	08/02/1999
8.	23/02/1999	23/02/1999
9.	25/03/1999	25/03/1999
10.	30/04/1999	30/04/1999
11.	20/05/1999	20/05/1999
12.	10/07/1999	10/07/1999

4.2.4 Growth measurements

Crop growth analysis was performed using five sequential destructive sample harvests viz. 21 January, 23 March, 17 May, 5 July and 30 August 1999, from pre-marked sample quadrats (2.5 m lengths x 4 rows). Crop growth analysis was carried out using the methodology described in Chapter 3.

4.2.5 Soil water content

At the final harvest, soil samples from 0 – 20, 20 – 40, 40 – 60 and 60 – 90 cm soil depths were taken to estimate the soil water content. The per cent water content was determined gravimetrically from the difference of the fresh and oven dry (at 105°C until constant weight) weight of soil and used to calculate profile soil water content. From these measurements, the plant available water content (PAWC) was determined by using various soil parameters (e.g. DUL, LL and BD) that were provided by Dr. M. Robertson (CSIRO Sustainable Ecosystems; personal communication). About 8 mm of rain was recorded just before the final harvest.

4.2.6 Green leaf N content

Green leaf N concentration was determined by the Kjeldahl digestion method followed by ammonium-nitrogen determination with an Auto-analyser (McLeod, 1982).

4.2.7 Data analysis

Data were analysed using procedures described in Chapter 3.

4.3 Results

4.3.1 Environmental conditions

From 'calendar' weeks 15 to 36 (winter months), the average maximum and minimum temperatures were 26.5°C and 14.6°C respectively (Fig. 4.1), with a mean of 21°C. These were similar to that of the average of maximum (26.4°C) and minimum (14.8°C) temperatures from 1991 to 1998 for Ayr, Burdekin (Fig. 4.1). The rainfall over the period, from week 1 to 35, was only 550 mm and the average daily solar radiation was 16.6 MJ m^{-2} for this period (Fig. 4.1).

4.3.2 Lodging and crop condition

The control treatment lodged in late March 1999, later than the usual conditions, i.e., February. The lodging event was very uniform in all the control plots, as the plants tended to lodge in the same way in the direction of the prevailing wind.

The scaffolding treatment again worked very well to keep the cane erect and maintain an undamaged canopy (Plate 4.2). However, late in the season, strong winds caused the stalks to lean against the scaffolding structure resulting in open canopies.

The combination of soil and aerial applications of insecticides worked very well against the cane grubs. Except for the mild occurrence of leaf rust in the early part of the season (October to February), no serious insect/pest was recorded during the season.

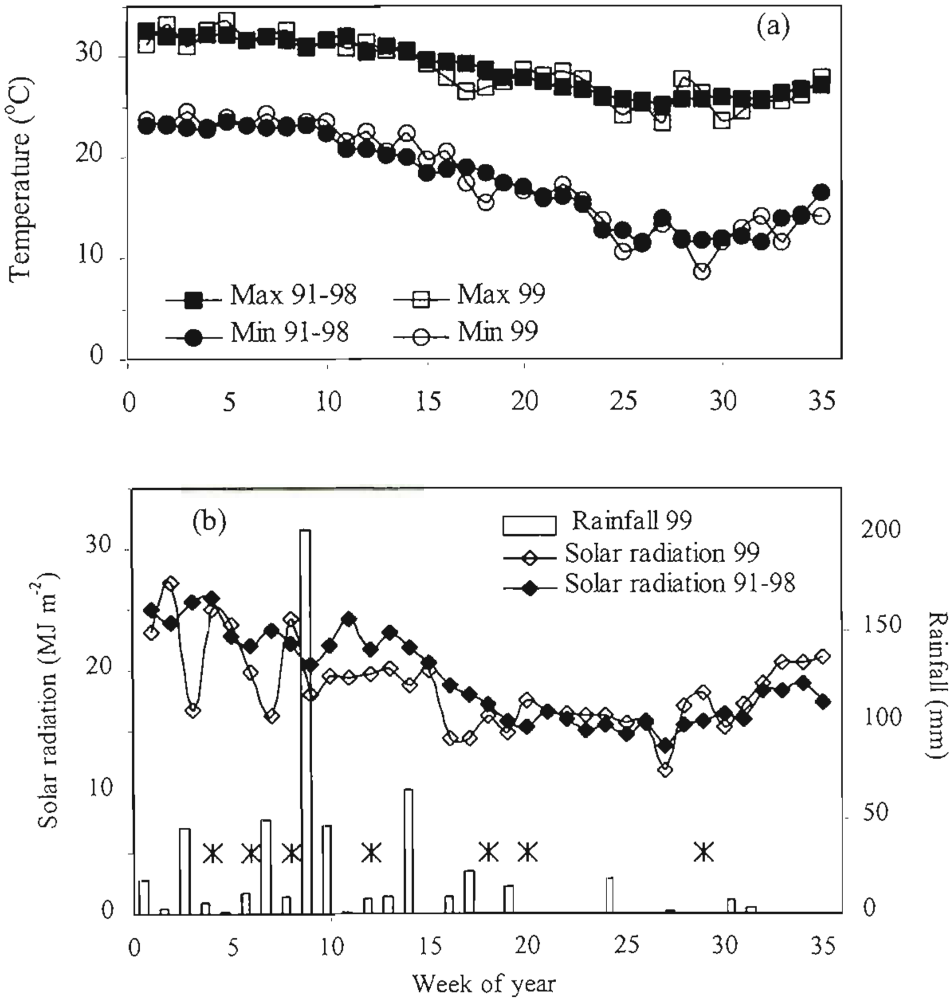

Fig. 4.1 Weather data (a) weekly means of daily minimum and maximum temperature at Ayr during 1999 and average of 1991 to 1998, and (b) daily solar radiation and total rainfall at Ayr during 1999. The symbol (ж) shows date of irrigation applications.

Plate 4.2 An aerial view of the control (1), scaffolding (2) and late crop (3) treatments designed to evaluate the 'yield plateau' in sugarcane at Ayr in 1998/99.

4.3.3 Soil water content

At the final harvest, the plant available soil water content (0 – 90 cm soil profile) was in the order of late crop > control > scaffolding treatment (Table 4.5). It was about 9%, 18%, and 47% of the total plant available water content for the scaffolding, control and late crop treatments respectively (Table 4.5). The lower plant available soil water content of the scaffolding and control treatments was probably due to higher evapotranspiration demand because of large crop sizes.

Table 4.5 Results of the plant available water content (PAWC) measured at the final sample of plant biomass at Ayr in 1998/99.

Treatment	Total PAWC (mm)	Actual PAWC (mm)
Control	87.0	15.9
Scaffolding	87.0	8.1
Late crop	87.0	41.0

4.3.4 Fresh cane yield

The accumulation of fresh cane yield in the scaffolding and control treatments slowed over the last two sample harvests, a period when the crop was partially stressed due to the normal practice of drying-off (~7 weeks) the soil prior to the harvest (Fig. 4.2a). However, compared with the scaffolding treatment, a marked decline in the rate of cane yield accumulation was observed in the control after lodging (Fig. 4.2a). At the final harvest, the scaffolding treatment produced significantly ($P \leq 0.05$) more (14%) fresh cane yield than the lodged control.

In the late crop treatment, the cane yield accumulation continued until the final harvest in August but again, a reduction was observed in the growth rate over the last two harvests (Fig. 4.2a).

4.3.5 Sugar content and yield

Compared with the scaffolding treatment, the rate of sugar accumulation slowed in the control treatment shortly after lodging (Fig. 4.2b). However, it recovered later during the period between the fourth and fifth sample harvests when similar rates of sugar accumulation were observed in all the three treatments (Fig. 4.2b).

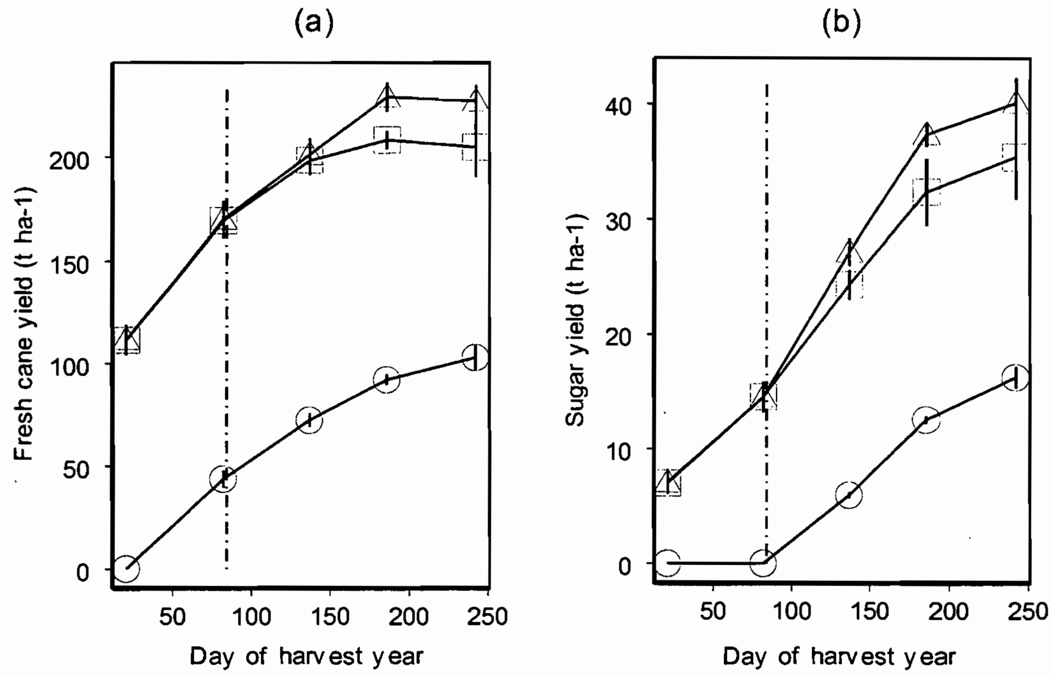

Fig. 4.2 Accumulation of (a) fresh cane and (b) sugar yields as affected by the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted lines show the date of lodging in the control treatment.

At the last three samplings, sugar yield in the scaffolding treatment was significantly higher ($P<0.05$) than that of the control (Fig. 4.2b). This was associated with differences in the CCS of live stalks and dilution effects from dead cane (Fig. 4.3a and 4.3b, Table 4.6) and differences in cane yield (Fig. 4.2a).

At the final harvest, the CCS of the scaffolding treatment was slightly higher than the control, but the difference was not statistically significant. However, both the control and scaffolding treatments produced higher ($P<0.05$) sugar yield than the late crop treatment at all the samplings due to their high cane yield and CCS contents (Fig. 4.2b).

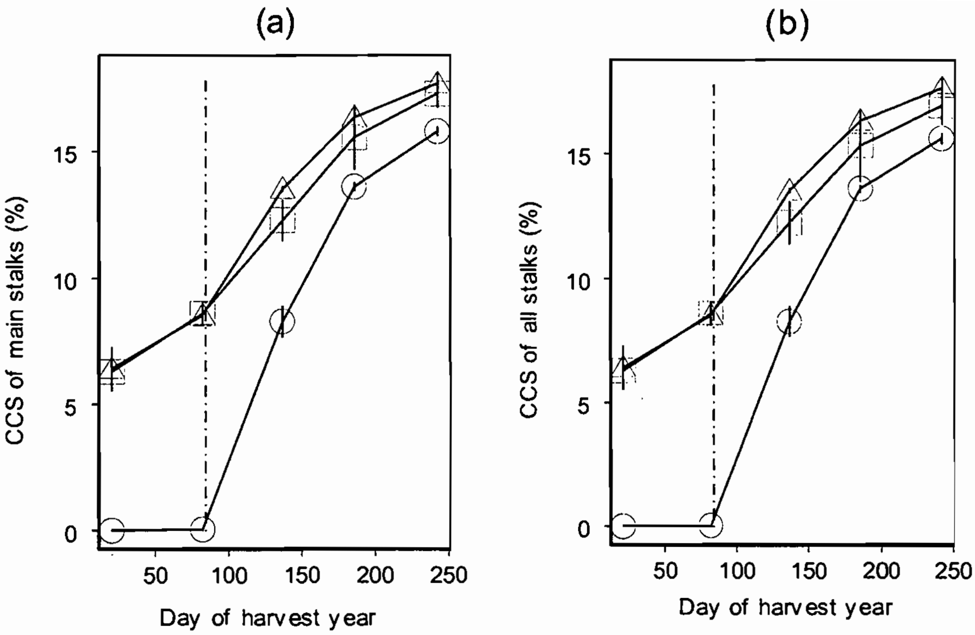

Fig. 4.3 Commercial cane sugar (CCS) content of (a) live primary stalks and (b) all stalks including dead or rat-damaged cane of the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

Table 4.6 Sugar content of live primary stalks as affected by different treatments and the dilution effects of dead and rat-damaged cane. Mean values followed by a common letter are not significantly different at the 5% level.

Date of harvest	CCS (%)					
	Live and sound cane			With dead and rat-damaged cane		
	Control	Scaffolding	Late crop	Control	Scaffolding	Late crop
21/01/99	6.3a	6.4a	*	6.3a	6.4a	*
23/03/99	8.6a	8.5a	*	8.6a	8.5a	*
17/05/99	12.3b	13.5a	8.3b	12.1b	13.5a	8.3b
05/07/99	15.5a	16.3a	13.6b	15.3a	16.3a	13.6b
30/08/99	17.3a	17.7a	15.8b	16.9a	17.6a	15.6b

* - Not measured

4.3.6 Biomass accumulation

Both the scaffolding and late crop treatments showed a linear increase in aboveground biomass for the periods between the first (22 January 1999) and fourth (July 1999) sample harvests (Fig. 4.4a). However, compared with the scaffolding treatment, the rate of aboveground biomass accumulation slowed in the control shortly after lodging (Fig. 4.4a). During the drying-off period, between the fourth and fifth sample harvests, a slowdown in aboveground biomass accumulation was observed in all the treatments (Fig. 4.4a). As discussed in more detail later, the slow-down in growth was most likely associated with the effects of water stress from the dry-down practice, rather than from other environmental effects like cooler temperatures or lower insolation.

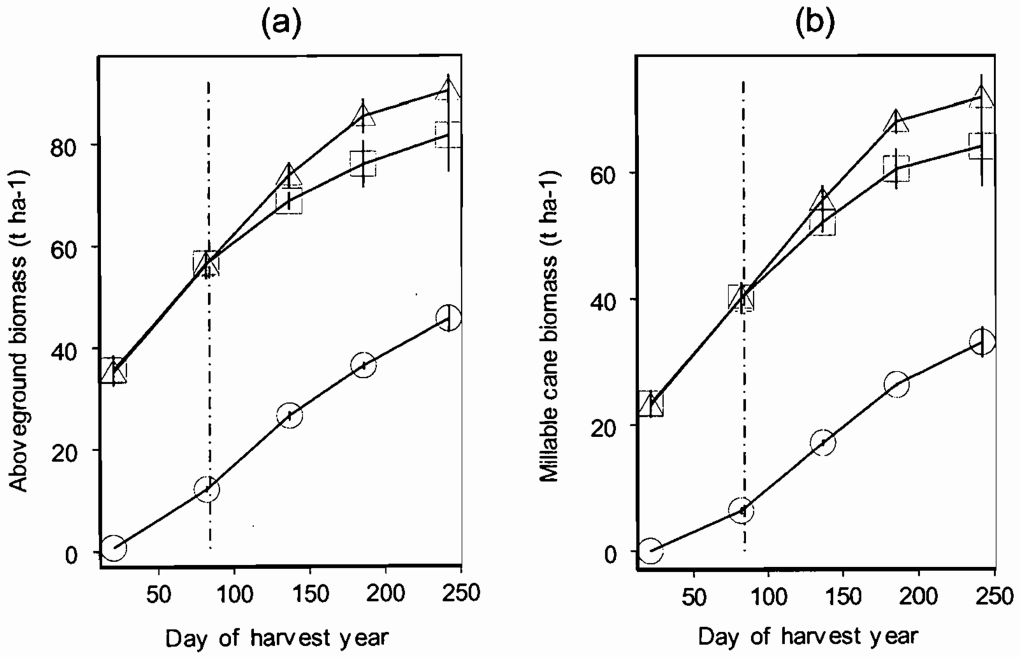

Fig. 4.4 Accumulation of (a) aboveground biomass and (b) cane biomass as affected by the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows date of lodging in the control.

The accumulation of biomass in the millable cane closely mirrored the accumulation of aboveground biomass. Again, shortly after lodging, a decline in the rate of cane biomass accumulation was observed in the control compared to the scaffolding treatment (Fig.

4.4b). At the final harvest, the scaffolding treatment produced significantly higher (14%) cane biomass than the control. The rate of cane biomass accumulation slowed in all the treatments between second last and last sample harvests, but none of the treatments experienced a plateau in cane biomass accumulation (Fig. 4.4b).

The green leaf biomass of the control and scaffolding treatments increased between the first two samplings and then declined over time until the final harvest in August due to leaf senescence (Fig. 4.5a). However, a much higher rate of decline was observed in the control compared to a gradual decline in the scaffolding treatment (Fig. 4.5a), resulting in lower LAI in the control (Fig. 4.11a). In contrast, the green leaf biomass of the late crop increased up to the third harvest and then changed little until the final harvest (Fig. 4.5a). At the final harvest, both the scaffolding and late crop treatments had a greater amount green leaf biomass than the control (Fig. 4.5a).

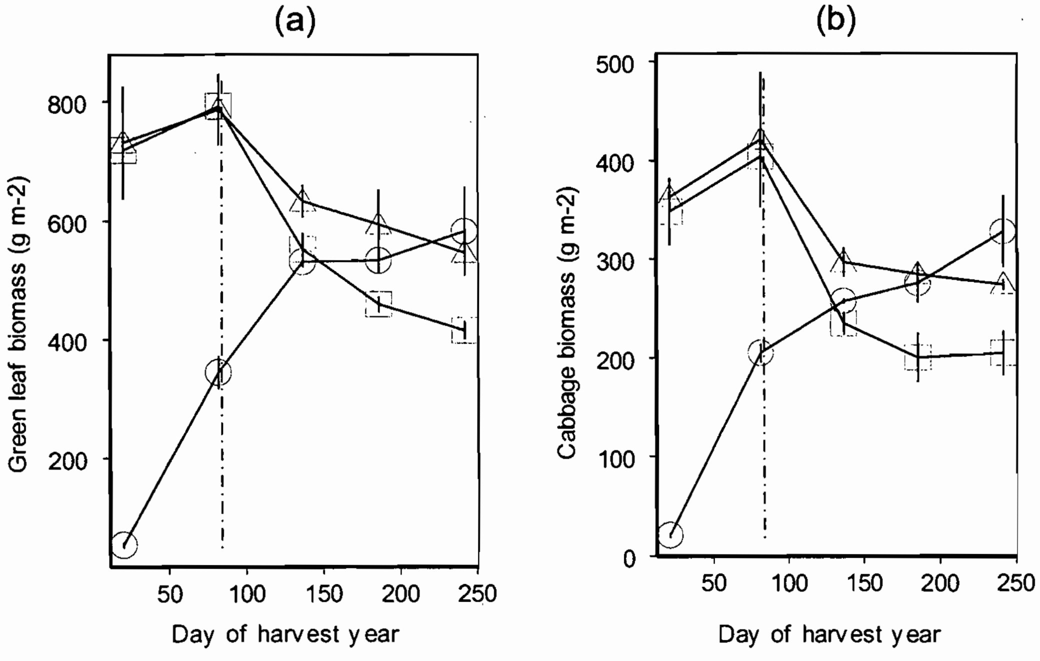

Fig. 4.5 Accumulation of green leaf (a) and cabbage (b) biomass as affected by the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

The pattern of accumulation of biomass in cabbage was almost identical to that of green leaf biomass accumulation in all the treatments (Fig. 4.5b). Trash biomass accumulation increased over time in all the treatments (Table 4.6a). Compared to the scaffolding or late crop treatments, dead cane biomass increased significantly over the last two harvests in the control (Fig. 4.6b).

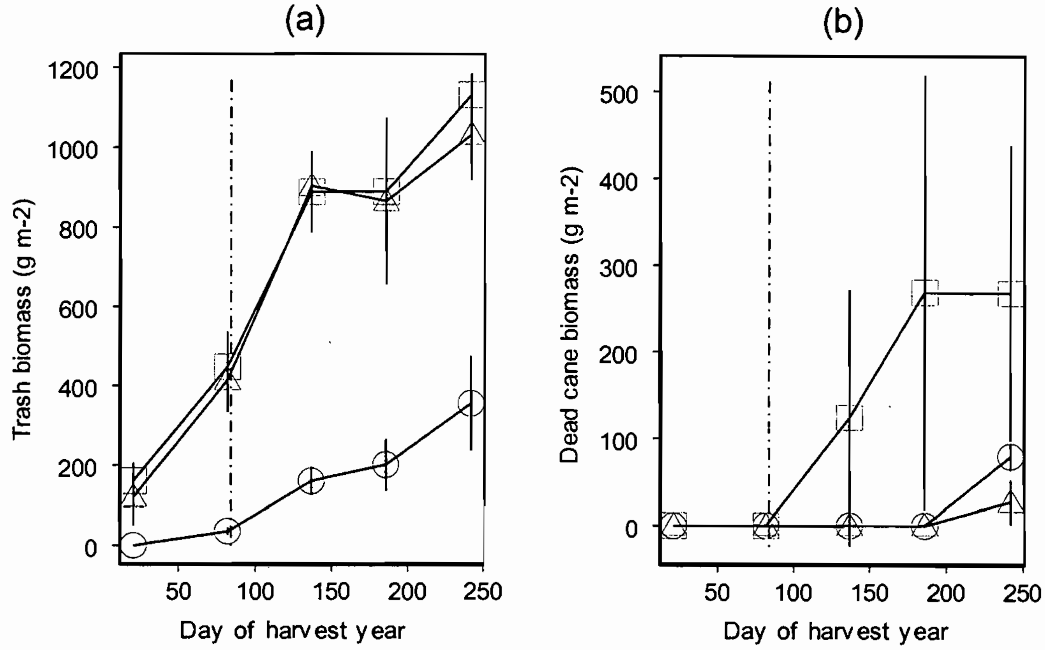

Fig. 4.6 Trash and dead cane biomass accumulation under the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

The three components (green leaf, cabbage and trash) only comprised 20 %, 22 % and 28 % of the total above ground biomass at the final harvest in the scaffolding, control and late crop treatments, respectively (Fig. 4.7).

Earlier in the growth period, the green leaf and cabbage components comprised a larger proportion of the total aboveground biomass, but the change in biomass of these components was small relative to the large change in millable cane biomass over time (Fig. 4.7).

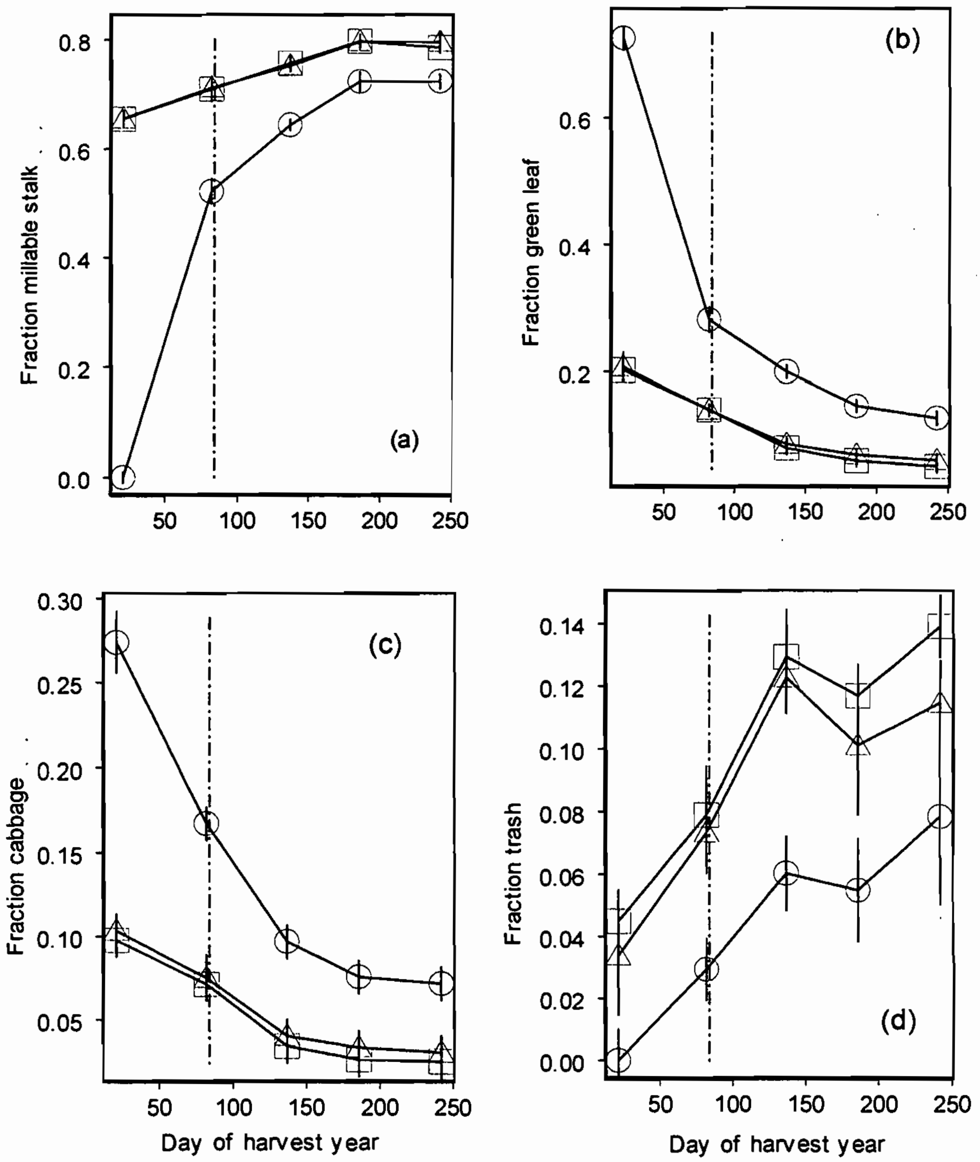

Fig. 4.7 Fraction of aboveground biomass as (a) millable stalk, (b) green leaf, (c) cabbage, and (d) trash components in the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

4.3.4 Stalk dynamics

Stalk number

No differences were observed in the initial stalk numbers between the scaffolding and control treatments (Fig. 4.8a, Table 4.7). However, within the scaffolding treatment, a higher (8.2 compared to 8.0 stalks m^{-2}) initial stalk number was observed at the second last harvest. A reduction in the number of live stalks was observed in the control treatment at the July and August sample harvests (Fig. 4.8b, Table 4.7).

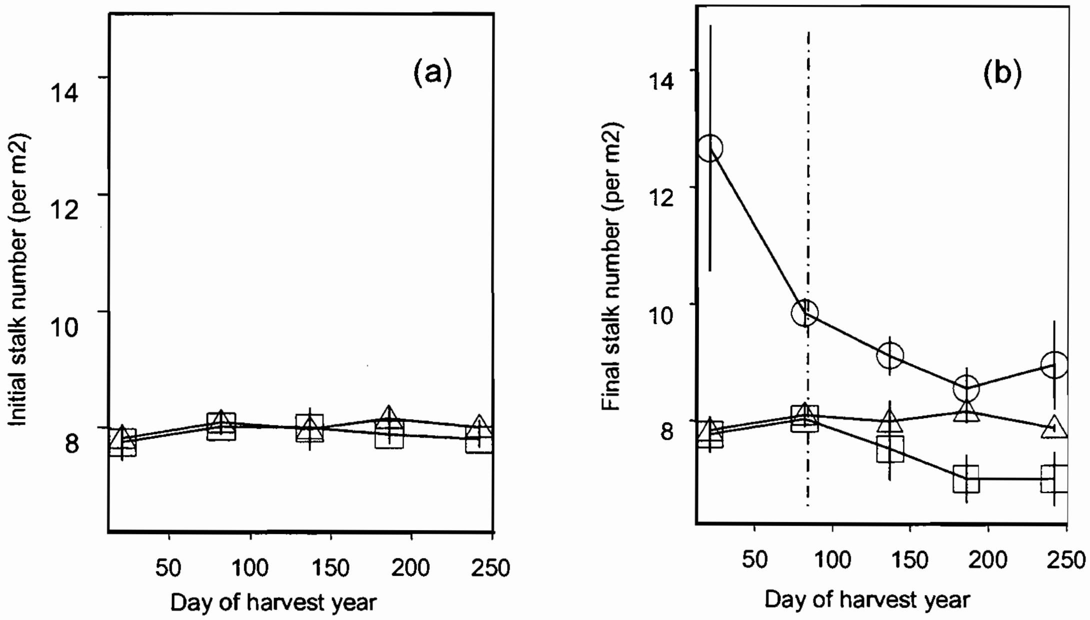

Fig. 4.8 Live stalk number as recorded (a) at the start of the experiment for each subsequent harvest area, and (b) at each sample harvest in the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

Table 4.7 Live (initial and final) and dead stalk number (for Control, C; scaffolded, S; and late crop, LC treatments) at Ayr during 1998/99. Mean values followed by a common letter are not significantly different at the 5% level.

Date of harvest	Stalk number (per m^2)								Sucker number (per m^2)		
	Initial		Final			Dead					
	C	S	C	S	LC	C	S	LC	C	S	LC
21/01/99	7.8a	7.8a	7.8b	7.8b	12.7a	0.0	0.0	0.0	0.0	0.0	0.0
23/03/99	8.0a	8.1a	8.0b	8.1b	9.8a	0.0	0.0	0.0	0.0	0.0	0.0
17/05/99	8.0a	8.0a	7.5b	8.0b	9.1a	0.5a	0.0b	0.0b	0.5a	0.0b	0.0b
05/07/99	7.9b	8.2a	7.0c	8.2b	8.6a	0.9a	0.0b	0.0b	0.5a	1.2a	0.0b
30/08/99	7.8a	8.0a	7.0c	7.9b	9.0a	0.8a	0.1b	0.5b	1.0a	1.0a	0.2b

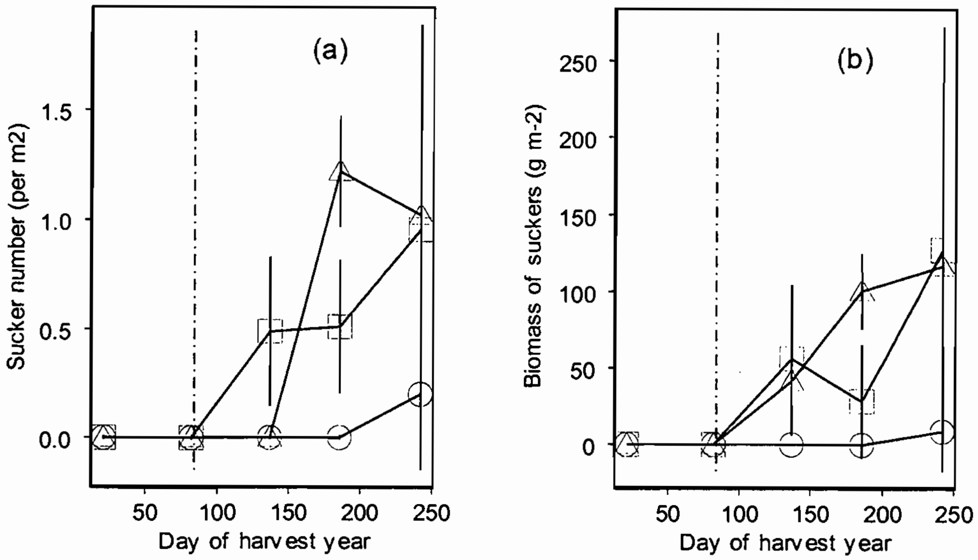

Fig. 4.9 Sucker (a) number, and (b) biomass as recorded in the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

The number of dead stalks was greater ($P<0.05$) in the control at the samplings conducted after lodging, apparently due to smothering effects. However, there was no net loss, i.e., complete disappearance of the stalks, such that stalks recorded in the quadrats before lodging were all accounted for (Table 4.7). The numbers and weight of the suckers were negligible in all the treatments (Fig. 4.9, Table 4.7).

Individual stalk growth

In all treatments, the aboveground biomass and millable cane biomass production per live stalk continued until the final harvest but a slowdown was observed later in the season (Fig. 4.10). However, at the sampling conducted after lodging in the control, the scaffolding treatment had significantly ($P<0.05$) more millable cane and total biomass per live stalk than the control treatment. The rate of dry matter production per stalk was slightly lower in the late crop treatment where stalks were growing at a higher density.

The individual stalk growth rate was highest for the period between March to May and then declined onwards in all the treatments (Table 4.8). However, the values for the period of 5 July to 30 August (second last to final harvest) were ranked in the order of scaffolding > lodged control > late crop (Table 4.8), clearly showing the independence of individual stalk growth from any effects of crop age. The differences in cane growth rates closely mirrored those in individual stalk growth rates (Table 4.8). The stalk growth rate declined, in all treatments, later in the season when, as noted above, the crops experienced some level of water stress from the drying-off practice.

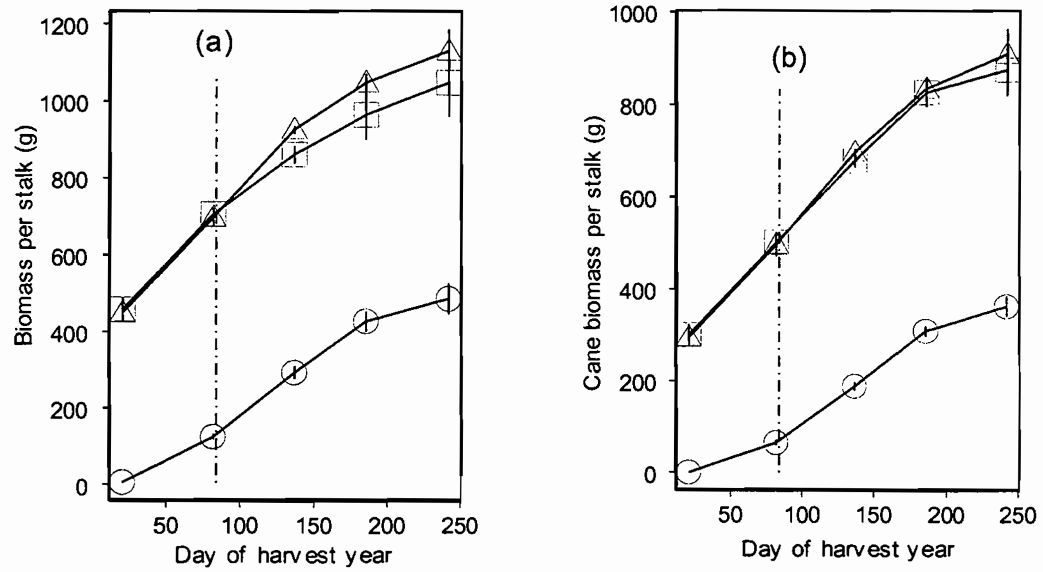

Fig. 4.10 Individual stalk biomass (a) total, and (b) cane as recorded in the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

Table 4.8 Live stalk growth (g stalk^{-1} day^{-1}) rate as affected by different treatments at Ayr in 1998/99. Mean values followed by a common letter are not significantly different at the 5% level.

Growth period	Cane growth rate (g stalk^{-1} day^{-1})			Stalk growth rate (g stalk^{-1} day^{-1})		
	Control	Scaffolding	Late crop	Control	Scaffolding	Late crop
Jan - Mar	3.27a	3.31a	1.07b	4.04a	4.05a	1.94b
Mar - May	3.22a	3.63a	2.24b	3.56a	4.17a	3.06b
May – Jul	3.08a	2.87a	2.50a	3.03a	2.53a	2.80a
Jul - Aug	0.89a	1.34a	0.95a	1.42a	1.73a	1.38a

Stalk elongation rate

Millable cane elongation followed a curvilinear relationship over time in all the treatments (Fig. 4.11a). No differences were observed in millable cane length between the scaffolding and control treatments except for the sampling conducted after lodging in the control, when the length of millable cane was significantly higher ($P<0.05$) in the scaffolding treatment.

In all treatments, the maximum rate of stalk elongation (SER; cm day^{-1}) was observed during the period between 1st and 2nd sample harvests and then declined over time later in the season (Fig. 4.11a). However, similar rates of stalk elongation in the scaffolding and late crop treatments later in the season indicated that this decline in SER was independent of crop age (Fig 4.11a). Again as noted earlier, the crop also suffered from some level of water stress before the second last harvest from lengthening of irrigation interval and then from drying-off before the final harvest. Consequently, the growth reduction was associated with an increase in cane dry matter content (Fig. 4.11b).

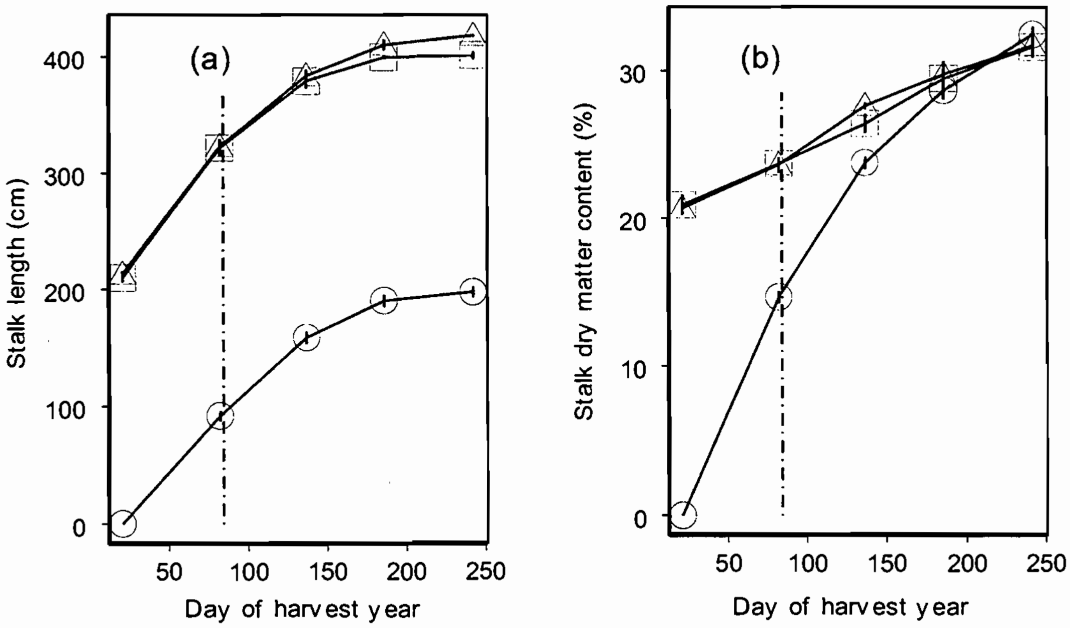

Fig. 4.11 Millable cane length (a), and dry matter content (b) with time in the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

4.3.8 Leaf area index

No differences were observed in the LAI of the control and scaffolding treatments before lodging occurred in the control (4.12a). Compared with the scaffolding treatment, a reduction in LAI was observed at the samplings conducted after lodging in the control. This was partially due to reduction in leaf area per stalk (4.12b) and partially due to reduced live stalk numbers (Fig. 4.8b). LAI was lower in the late crop treatment except for the July and August samplings, when it was similar to the control and then the scaffolding treatment (Fig. 4.12a).

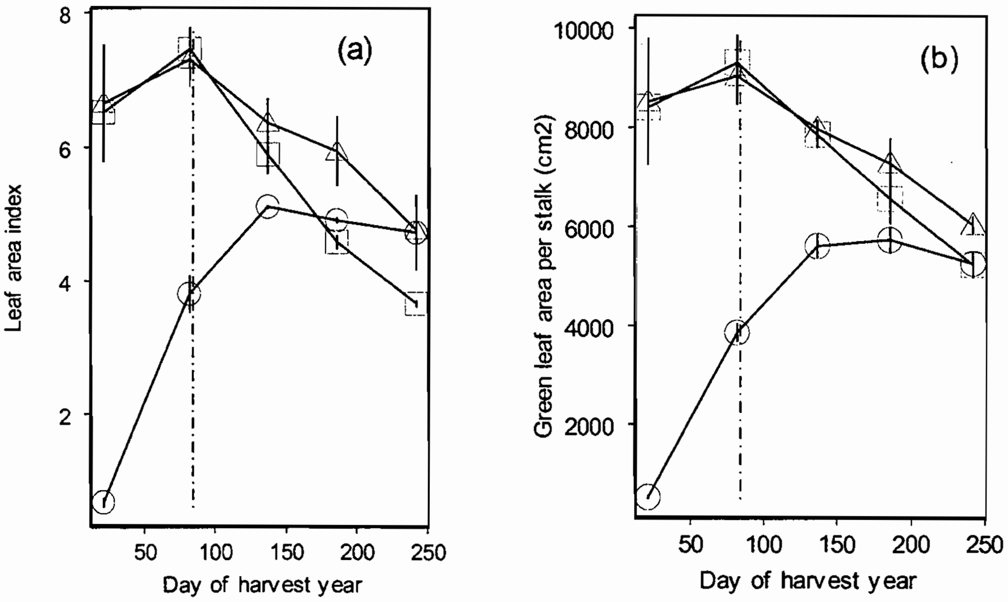

Fig. 4.12 Green leaf area index (a), and leaf area per stalk (b) with time for the control (squares), scaffolding (triangles) and late crop (circles) treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

4.3.9 Green leaf N content

In all the treatments, green leaf N concentration was highest (about 0.015 g N g^{-1}) at the March (2^{nd}) and May (3^{rd}) sample harvests (Fig. 4.13). A slight decline was observed in green leaf N concentration at the July (4^{th}) harvest in all the treatments (Fig. 4.13). At the final harvest in August, green leaf N concentration had declined rapidly in all treatments to a value of 0.009 g g^{-1} (Fig. 4.13). The values of green leaf N concentration observed at the final harvest were well below the values observed in some previous studies (e.g. Wood *et al.*, 1996). This rapid decline in leaf N content might be associated with the effects of water stress such as reduced up-take from the dry-down practice before the final harvest.

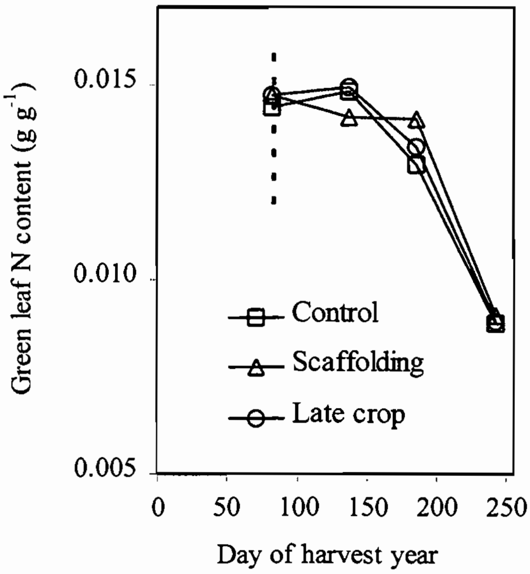

Fig. 4.13 Green leaf N concentration with time in different treatments designed to establish the cause of the 'yield plateau' at Ayr during 1998/99. Dotted line shows the date of lodging in the control treatment.

4.3.10 Radiation interception and RUE

For the period between the first and second samplings, the measured fractional radiation interception (*fi*) was more than 0.90 for the control and scaffolding treatments (Fig. 4.14b). In the scaffolding treatment, the value of *fi* changed little until mid July when strong winds caused some leaning of the plant tops, resulting in *fi* values less than 0.80. However, a reduction in *fi* was observed in the control following lodging in late March (Fig. 4.14b). The *fi* of the late crop treatment was very low (0.32) at the first harvest, but increased over time to a value of 0.84 by April and then was similar to that of the control, but remained lower (by about 5%) than the scaffolding treatment until mid July.

For the first four samplings, the relationship between aboveground biomass accumulation (g m^{-2}) and cumulative solar radiation intercepted (*Si*; MJ m^{-2}) from the first sample harvest was linear for the scaffolding and late crop treatments (Fig. 4.14a). Compared to the scaffolding and late crop treatments, the poor relationship in the control was probably due to the shading effects as a result of clumping of the stalks and overlapping of the green leaves after lodging occurred.

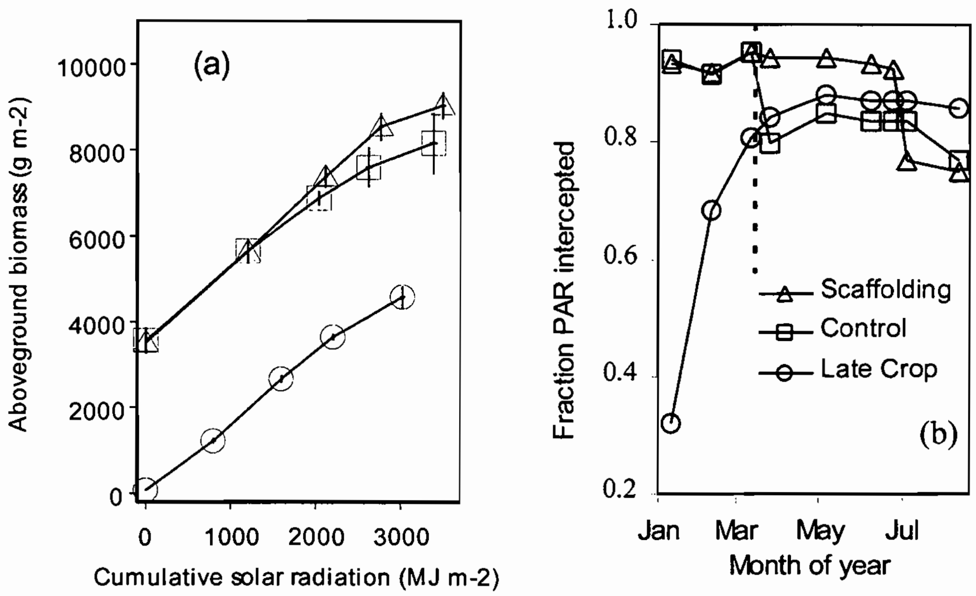

Fig. 4.14 Relations showing (a) aboveground biomass accumulation and solar radiation intercepted, and (b) fraction of radiation intercepted over time from the first sample harvest, in the three treatments. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

For the period between the first and second samplings (January to March), the calculated RUE was 1.74, 1.76 and 1.45 g MJ^{-1}, for the control, scaffolding and late crop treatments, respectively. The maximum values of RUE were recorded between March and May for the scaffolding (1.92 g MJ^{-1}) and late crop (1.78 g MJ^{-1}) treatments. Compared to the scaffolding treatment, a reduction in RUE was observed in the control shortly after lodging (Fig. 4.14a). However, a sharp decline in RUE was observed in all the treatments at the final harvest (Fig. 4.14b), which corresponded to the decline in green leaf N concentration of the crops (Fig. 4.13).

For the entire experimental period, from the first sample harvest to final sample harvest, the calculated RUE values were in the order of scaffolding > late crop > control treatment. The mean values of RUE were 1.58, 1.49 and 1.36 g MJ^{-1} m^{-2} for the scaffolding, late crop and control treatments respectively.

4.3.11 Summary of results for the dry tropics trial

Based on comparison of the scaffolding and late crop treatments, right up to the final harvest, there was no evidence that crop age might be implicated in any slowdown of growth. For almost every attribute of growth that was measured, the growth of the older scaffolded crop treatment was similar to that of the late crop treatment. Indeed, compared to the scaffolding treatment, rates of dry matter and sucrose production per live stalk were slightly lower in the late crop treatment where stalks were growing at a higher density.

Consistent with the experience in the wet-tropical environments, lodging again had a detrimental impact on crop growth, sucrose accumulation and sugar yield under the irrigated conditions of the dry tropics. Lodging affected a number of growth and yield attributes such as live stalk number, live stalk CCS, LAI, RUE, stalk length and the accumulation of live stalk biomass (total and millable cane). The effects of lodging on the sugar concentration were greatest immediately after lodging, while the effects on cane and sugar yield were present and sustained throughout the growth after lodging.

Compared to the scaffolding treatment, there was a reduction of 13% in sugar yield in the lodged control at the final harvest. The yield reductions associated with lodging were mainly the result of lower cane biomass (about 11%) and lower sugar content of the live stalks (about 2%). There was an additional dilution effect on CCS in the control from the low sugar concentration of the dead cane, depending on the amount of dead cane. The dead stalks had a CCS of between 7.0 and 7.4 units lower than live stalks of the control and scaffolding treatments. Consequently, the mean CCS of all live and dead millable stalks in the lodged control was 0.33 units lower at the final harvest, a commercially quite significant outcome.

The reduction in cane biomass following lodging was mainly due to death (up to 0.9 stalk m^{-2}) of stalks due to smothering or to stalk breakage. At the harvests conducted after lodging, compared to the scaffolding treatment, a slowdown in biomass growth per live stalk was also observed in the control. This can be related to reductions (up to 10%, compared with the scaffolding treatment) in radiation interception as a result of the disruption of the crop canopy and a decrease in LAI from increased leaf senescence. There was also a reduction in RUE after lodging in the control.

Lodging resulted in a slowdown in cane biomass accumulation that was not as large as that observed by Muchow *et al.* (1995). This may have been due to a reduced level of stalk death due in turn to differences in timing/nature/extent /frequency of the lodging observed in this study compared to the previous studies. Unlike the previous studies (Muchow *et al.*, 1995), there was no 'net' loss, i.e., complete disappearance of stalks with all the live and dead stalks being accounted for.

In all treatments, biomass production continued until the final harvest. However, one concern was the slowdown of growth in all treatments before the final harvest, during the drying-off period. Compared to the scaffolding and control treatments, the crop growth slowed much less in the late crop treatment, probably because there was more water available. At the final harvest, the recorded available soil water content was only 9% and 18% for the scaffolding and control treatments respectively. In contrast, the late crop treatment had available soil water content of about 47%. Sugarcane growth is known to be highly sensitive to water stress (Mallik and Venkataraman, 1958). From a field study, Singh and Reddy (1980) concluded that a reduction from 60% to 20% in available soil moisture content affected cane growth, yield and juice quality. They further observed that plant height and leaf development was more sensitive to moisture stress than the rate of leaf emergence. More recently, Inman-Bamber and de Jager (1986 and 1988), from rain sheltered field experiments in South Africa, reported that imposition of water stress resulted in substantial reductions in both, stalk elongation and leaf extension rate. They further observed that the effects of water stress on stalk growth were reversible. However, imposition of water stress affected the development of cane and sucrose yields differently due to differential responses of plant extension and stomata to water stress (Inman-Bamber and de Jager, 1985). Under moderate stress over a long period, growth is reduced more than photosynthesis and consequently dry matter content may increase sufficiently to offset the effect of cane yield reduction on sucrose yield. However, stomatal closure from severe water stress can halt the increase in dry mass of stalks (Inman-Bamber and de Jager, 1988).

In the scaffolding treatment, apart from the apparent water stress, spatial stalk variation was also a possible factor that contributed to the slowdown or reduction of RUE of the crops. The measured initial stalk number was higher (0.2 stalk m^{-2}) at the second last harvest than the last harvest. However, if it were assumed that there was no actual difference in stalk numbers between the second last and last sample harvests, RUE during the last two sample harvests would have been 1.1 g MJ^{-1}, 45% higher than that actually measured. Even so, in the absence of any other constraints, RUE of the crop should have been of the order of 1.7 g MJ^{-1}, as observed in previous studies (e.g. Muchow *et al.*, 1994a). This indicated that some other factor(s), such as water stress/N stress/cool temperature, contributed to a reduction (about 35%) in RUE of the scaffolding crop between the last two sample harvests.

In order to further explore the cause(s) of the late 'slowdown' in crop growth in all three treatments, it was decided to evaluate the responses observed in the Ayr experiment using crop simulation modelling. The aim was to assess and quantify the potential impact of water stress on crop growth and yield accumulation, to establish the likelihood that it was water stress, as hypothesised, and not some other seasonal factor, that caused the later growth slowdown. To this end, a separate analysis (simulation studies) was performed using the crop growth simulation model APSIM-Sugarcane, developed for sugarcane by Keating *et al.* (1999). A brief overview of the model (APSIM-Sugarcane) and the simulation output results are presented in the next section (section 4.4: Simulation studies).

4.4 Simulation studies

4.4.1 Introduction

In the Ayr, 1998/99 experiment, there was a slowdown in biomass production in all three treatments between the last two sample harvests. As discussed above, lodging partially contributed to this effect in the control, but some other factors (e.g. water stress/N stress/cool temperature) were involved in the scaffolding and late crop treatments.

In the Ayr experiment, the irrigation interval was lengthened in July and there was a drying-off period of more than seven weeks before the final harvest. From the soil water content data, presented in the previous section, it was evident that the crops experienced some level of water stress.

4.4.2 Model overview

APSIM-Sugarcane simulates sugarcane crop growth on a daily time-step basis in relation to climate, water and nitrogen. A detailed description of the module is given by Keating *et al.* (1999).

In APSIM-Sugarcane, crop dry weight accumulation is driven by the conversion of intercepted radiation to biomass, via RUE. RUE is reduced whenever extremes of temperature, soil water shortage or excess, or plant nitrogen deficit limit photosynthesis. The crop canopy, which intercepts radiation, expands its area as a function of both time and temperature, and can also be limited by extremes of temperature, soil water shortage or excess, or plant nitrogen deficit. Biomass is partitioned among various plant components (leaf, cabbage, structural stem, roots and sucrose) as determined by crop phenological stage.

In the absence of nitrogen or water stress, thermal time (TT, °C days) is used to drive phenological development and canopy expansion. Thermal time is calculated by using a base temperature of 9°C, optimum temperature of 32°C, and maximum temperature of 45°C. Five phenological stages are used in the model: planting, sprouting, emergence, beginning of stalk growth and flowering. Sugarcane produces flowers but, at this stage, flowering as a phenological phase is deactivated in the model due to lack of information on precise mechanisms (Keating *et al.*, 1999). The APSIM-Manager (McCown *et al.*, 1996) can initiate lodging, a common phenomenon in well grown sugarcane crops, in response to any aspect of the system state (e.g., crop size, time of year, weather). APSIM-Sugarcane responds to lodging via a specified rate of stalk death derived from earlier field experimentation (e.g. Muchow *et al.*, 1995). The dead stalk biomass is added to the 'dead biomass' pool and is included in cane and above ground biomass totals. This is just an approximation to the overall decline in biomass accumulation associated with various lodging effects such as reduction in cane weight and sugar content due to reduced leaf area index and radiation interception and some level of stalk death after lodging.

The model responds to water stress through reductions in rate of leaf expansion and RUE of the crop. Water stress in the model reduces the rate of leaf area expansion and RUE, via two soil water deficit factors (SWDEF), which may vary from 0.0 to 1.0

(Keating *et al.*, 1999). SWDEF_PHOTO, which is less sensitive to drying, reduces the RUE (i.e., net photosynthesis) and transpiration, below its maximum. SWDEF_EXPANSION is more sensitive to soil drying and reduces the rate of processes governed primarily by cell expansion, i.e., daily leaf area expansion. Both, SWDEF_PHOTO and SWDEF_EXPANSION are calculated as functions of the ratio of potential soil water supply from the root system and the transpiration demand.

4.4.3 Crop growth simulation at Ayr, 1998/99

The model was configured to represent the Ayr trial (1998/99) using the experimental methodology and crop management practices, as described in the previous section. Some of the soil parameters such as DUL, LL and BD were taken from a previous study, i.e., 'SUGARBAG[1]' Experiment ID 42 that was conducted on the same block of land (Dr M. Robertson, CSIRO Sustainable Ecosystems; personal communication). The model was run for a cycle of about 4 to 5 years before the actual experiment period to ensure equilibrium conditions prevailed at the commencement of the experimental period, i.e., April 1998 to August 1999. The crop was planted on 18 April 1998 and harvested on 30 August 1999. The results for two treatments, lodging and scaffolding, were for the plant crop. The third treatment, i.e., the 'late crop' was ratooned on 16 December 1998 and crop growth was simulated for a first ratoon (R1) crop. For all treatments, initial stalk numbers were adjusted according to the observed stalk numbers, i.e., 8 stalk m^{-2} for the control and scaffolding treatments and 8.5 stalk m^{-2} for the late crop treatment. In the control, lodging was triggered in response to the actual time (e.g. 25 March 1999) of lodging.

The model was run for two situations:

a.) With the crop management and irrigation regime imposed as for the experimental conditions; and then

b.) With as for (a) but with additional irrigation during the drying-off period.

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[1] A Database System for Sugarcane Crop Growth, Climate, Soils, and Management Data - CSIRO Tropical Agriculture.

4.4.4 Results

The key factors and aspects of crop development examined were N and water stress factors, stalk dynamics and aboveground and millable cane biomass accumulation for all the treatments.

4.4.4.1 Water and N deficit factors

The model output indicated that there was no evidence of the occurrence of any N stress in the scaffolding treatment during growth (Fig. 4.15). The modelled value for this parameter remained at 1.0 throughout the crop growth period. Similarly, there was no occurrence of any N stress in the control and late crop treatments.

In contrast, the simulations using the actual experimental crop management and irrigation regime indicated that the scaffolding treatment experienced a severe water stress late in the season, e.g. between 415 to 500 DAP (Fig. 4.16). The value for this parameter fell considerably below 1.0 toward the last harvest. There was also an early season water stress at about 280 and 300 DAP, but it was relieved after an irrigation application and/or rain during that period. This simulated water stress, especially the late season water stress, corresponded well with the visual observations and also reflected from the measurements of plant available water content at the final harvest.

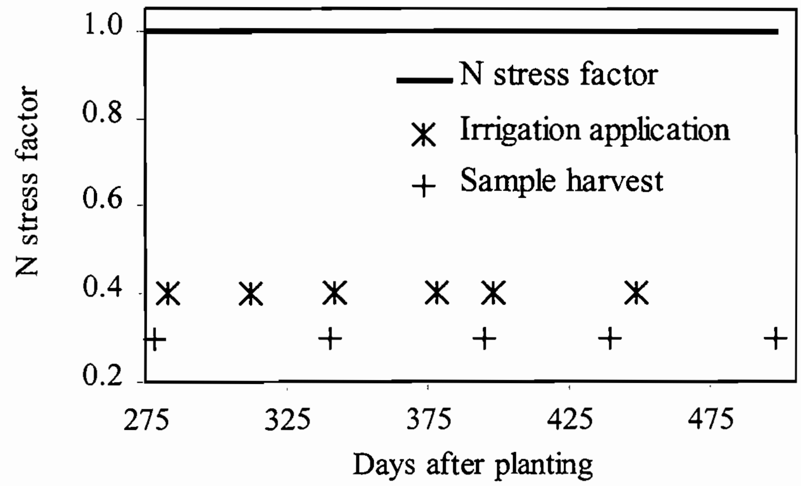

Fig. 4.15 Modelled response of the N stress factor (NFACT_EXPANSION) for the scaffolding treatment at Ayr in 1998/99.

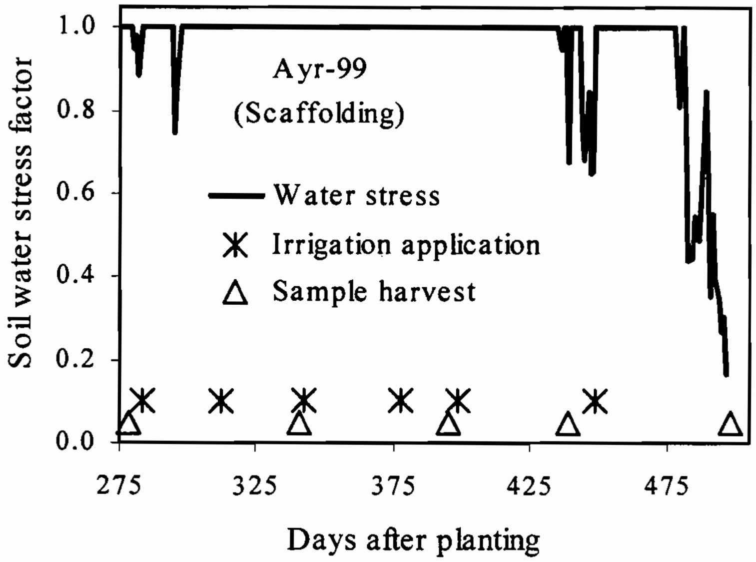

Fig. 4.16 Modelled response of the water stress factor (SWDEF_EXPANSION) for the scaffolding treatment at Ayr in 1998/99.

Similarly, the model indicated that there was late season water stress in the control, between 415 to 500 DAP, and in the late crop treatment between 180 to 257 DAR. This simulated water stress was removed by simulating the application of additional irrigation during the stress periods. The simulated impact of the water stress on biomass accumulation was estimated by comparing the growth simulations with and without the late irrigation.

4.4.4.2 Biomass accumulation

With the crop management and irrigation regime as for the experimental conditions

The simulations of the time-course of aboveground biomass and millable cane biomass for the control and scaffolding treatments were reasonably close to those observed, especially for the late season growth (Fig. 4.17a and b).

However, the decline in the rate of simulated cane biomass accumulation towards the end of the season was not as substantial as observed in reality. This was probably due to a discrepancy in the dry matter partitioning of trash and millable cane components between the model and in reality (Fig. 4.18). The model tended to under-estimate the trash components later in the season. Nevertheless, the model output indicated two late season slowdowns in aboveground and cane biomass accumulation (Fig. 4.17a and b) corresponding to the simulated periods of water stress (Fig. 4.16). The control treatment lodged at 341 DAP and the model response was to slowdown the rate of biomass accumulation in this treatment (Fig. 4.17a).

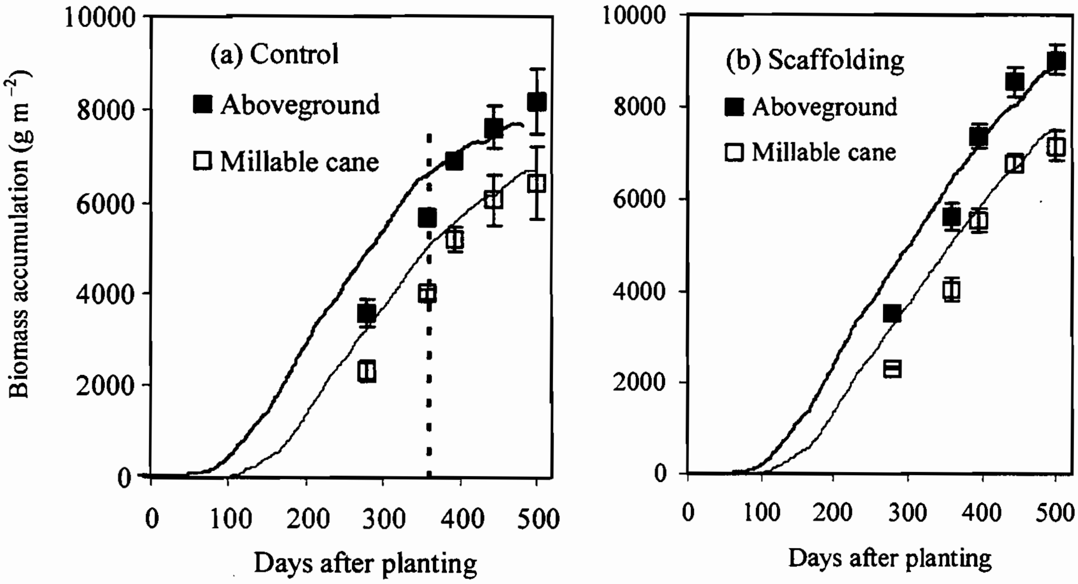

Fig. 4.17 Time courses of modelled (lines) and observed (symbols) biomass accumulation in the control and scaffolding treatments at Ayr in 1998/99. Bars represent ± SE of the means and the dotted line shows the date of lodging in the control treatment.

In the case of the late crop treatment, the model under-predicted the biomass (cane and aboveground biomass) accumulation for all the samplings (Fig. 4.19). This was probably due to some discrepancy in phenological development between the model and in reality, as the predicted as well as the observed biomass production followed similar trends. One of the reasons for this could be that this crop was ratooned at an early stage (active-tillering phase) and bud sprouting and crop development took place at a faster rate than for a normal ratoon crop. There could be other reasons as well, such as the model was validated only for crops ratooned by machine harvest not for hand harvested crops as was the case in this experiment. The model output for the late crop treatment also showed two small slowdowns in the aboveground biomass and cane biomass accumulation (Fig. 4.19), which again corresponded to putative water stress periods.

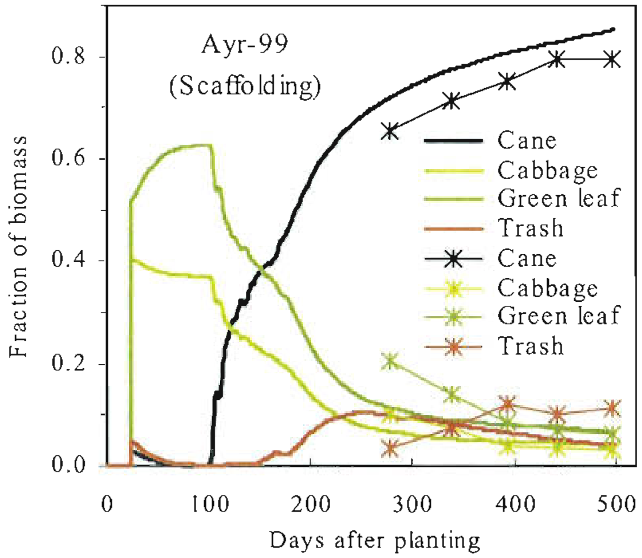

Fig. 4.18 Time courses of modelled (lines) and observed (lines with symbols) fraction of biomass as various components, in the scaffolding treatment at Ayr in 1998/99.

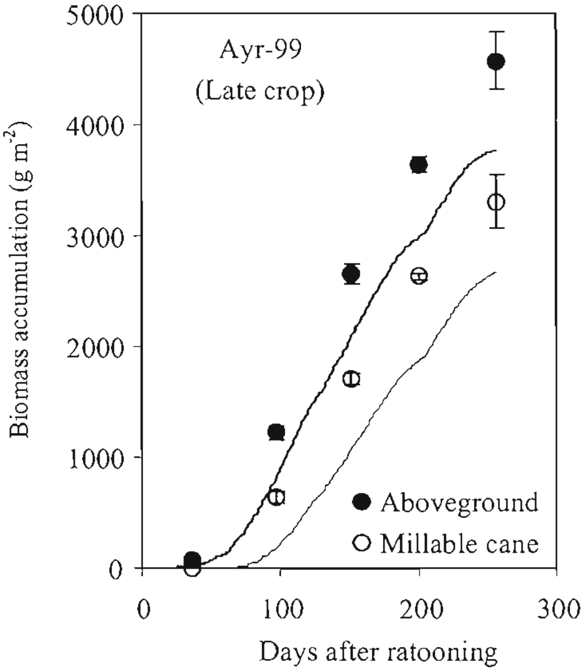

Fig. 4.19 Time courses of modelled (lines) and observed (symbols) biomass accumulation in the late crop treatment at Ayr in 1998/99. Bars represent ± SE of the means.

With additional irrigation during the drying-off period

The simulated removal of late season water stress resulted in an increase in aboveground biomass production in all three treatments (Fig. 4.20a, 4.21a and 4.22a). A similar increase was observed in the millable cane biomass production in the treatments after the simulated removal of the water stress (Fig. 4.20b, 4.21b and 4.22b).

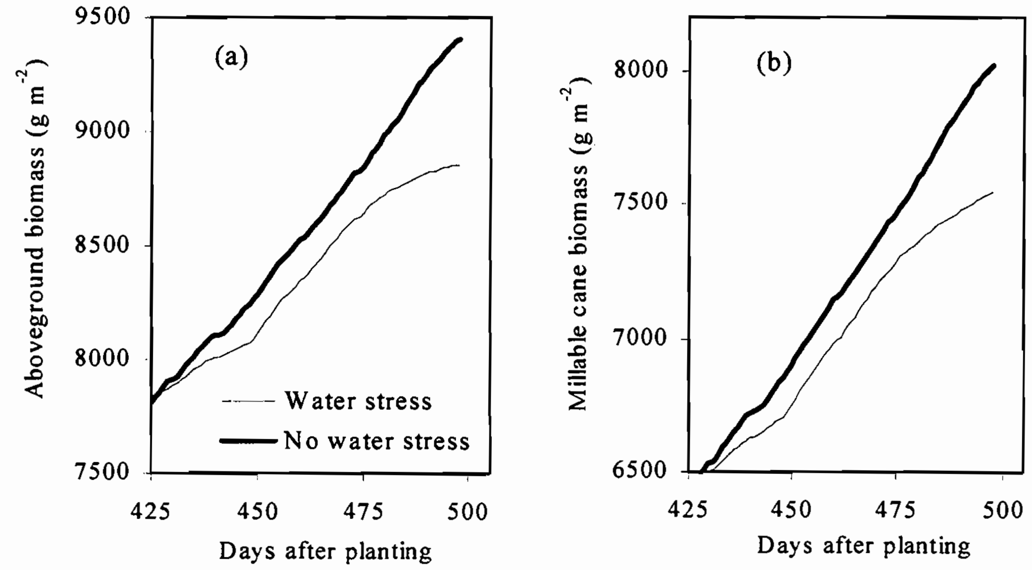

Fig. 4.20 Time courses of modelled (a) aboveground and (b) millable cane biomass accumulation, with and without water stress, in the scaffolding treatment at Ayr in 1998/99.

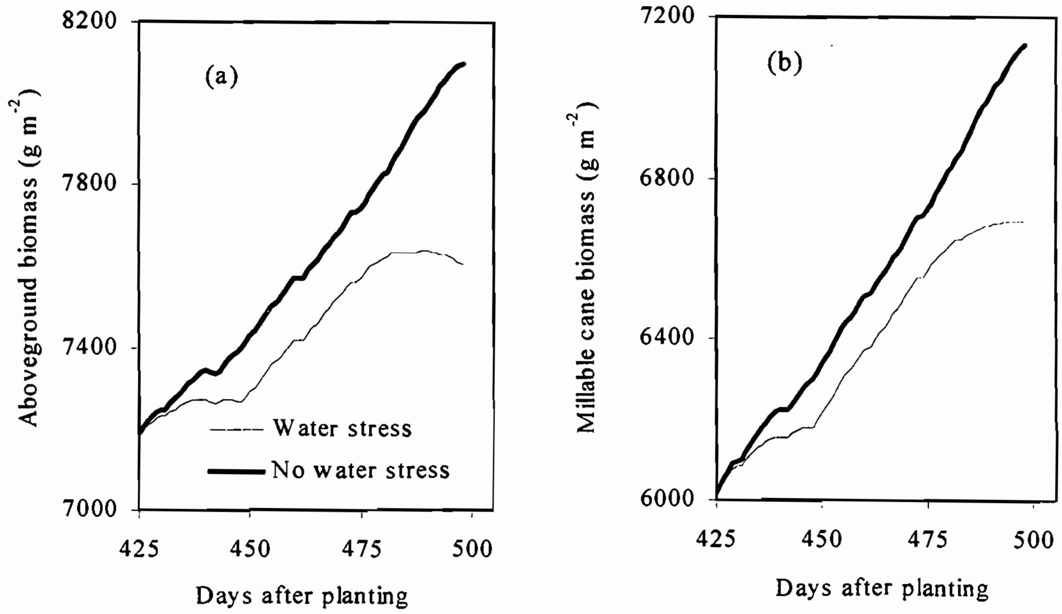

Fig. 4.21 Time courses of modelled (a) aboveground and (b) millable cane biomass accumulation, with and without water stress, in the control treatment in Ayr 1998/99.

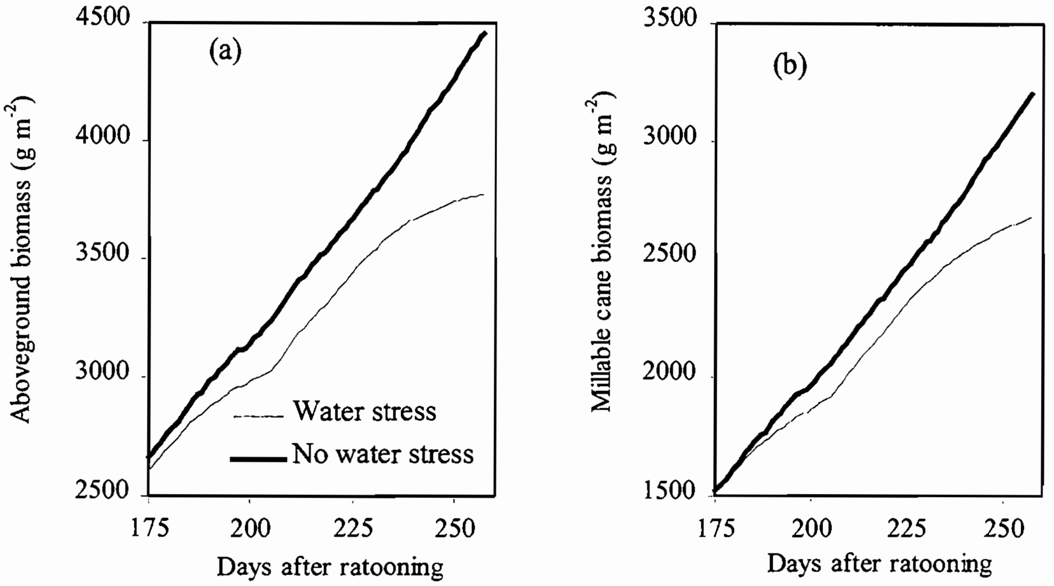

Fig. 4.22 Time courses of modelled (a) aboveground and (b) millable cane biomass accumulation, with and without water stress, in the late crop treatment at Ayr in 1998/99.

Table 4.9 Observed and modelled values of RUE (g MJ^{-1}) for the last two sample harvests for the scaffolding treatment at Ayr during 1998/99.

S No.	Scenario	RUE
1.	Potential (without any constraint)	1.7
2.	Observed	0.6
3.	Calculated (eliminating stalk variation)	1.1
4.	Modelled (experimental conditions)	1.1
5.	Modelled (no water stress)	1.7

4.4.4.3 Summary of the simulation results

The evidence from the simulation studies was consistent with the hypothesis that all the treatments experienced a severe water stress later in the season, i.e., before the last irrigation (Mid July) and before the final harvest. The simulated removal of this late season water stress increased both cane and aboveground biomass production in all the treatments. This late season water stress contributed to about a 35% reduction in RUE in the scaffolding treatment between the last two sample harvests. For the last two sample harvests, the simulated (as per experimental conditions) value of RUE for the scaffolding treatment was well in agreement with the calculated value of RUE over the same period when spatial stalk variations were eliminated.

Overall, the model simulated the large crops reasonably well late in the season under both lodged and non-lodged conditions. There was a good agreement between the simulated and measured values for different growth parameters, especially the late season aboveground biomass production. However, in the case of cane biomass, some discrepancies emerged between the simulated and measured yields in the later stages of the crops, probably due to inadequate modelling of dry matter partitioning for cane and trash components.

Currently, the model accommodates the combined effects of lodging such as reduction in LAI, radiation interception, biomass and sugar accumulation and stalk death, only via a specified rate of stalk death (Keating *et al.*, 1999). However, large differences were observed between the modelled (0.017 stalk m^{-2} day^{-1}) and measured (0.006 – 0.010 stalk m^{-2} day^{-1}) rates of stalk death due to lodging (Fig. 4.23).

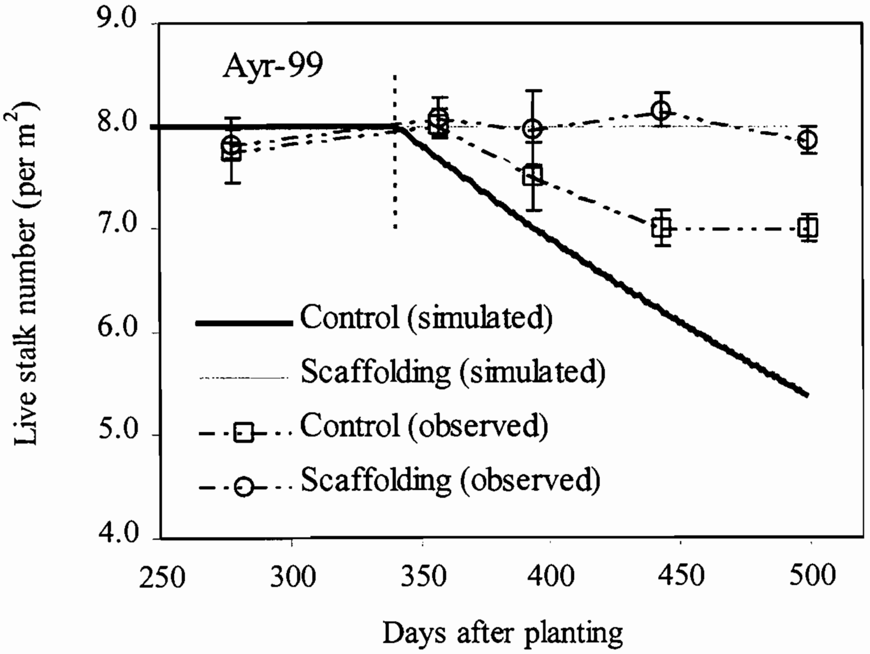

Fig. 4.23 Observed and simulated number of live stalks in the control and scaffolding treatments. Bars represent ±SE of the means. The dotted line shows the date of lodging in the control treatment.

Clearly, there is potential to enhance the model capability to simulate the impact of lodging on cane and sugar yield. To address this issue, first there is a need to incorporate the various effects of lodging on different crop growth parameters in the model and then calibrate the model against a range of data sets, where lodging was experienced. These crop growth parameters include:

1. About a 50% reduction in the rate of stalk death due to lodging i.e., from 0.02 to 0.01 stalk m^{-2} day^{-1};

2. A reduction in LAI or an increased rate of leaf senescence after lodging and ultimately the addition of this biomass to the trash pool;

3. A reduction of about 10% in radiation interception after lodging;

4. A reduction in stalk weight or RUE after lodging; and

5. A reduction in dry matter partitioning towards the sucrose pool for a short time after lodging and then a recovery to original values over time, depending on the timing, frequency and intensity of the lodging event.

There was one more significant discrepancy, and that was in the dry matter partitioning between the cane and trash components, especially at the later growth stages. Currently, the model tends to under-estimate the trash biomass and over-estimate cane biomass, and hence sugar yield, during later growth periods. To address these issues and to initiate the process of model improvement, a framework for interpreting lodging effects on yield (see Appendix II) has been submitted to APSIM-Help for consideration to incorporate in the APSIM sugar module.

Chapter 5 Conclusions and inferences to be drawn from the field studies

5.1 Introduction

In the preceding two chapters, data were presented on the effects of treatments designed to test competing hypotheses on the causes of an observed 'slowdown' in biomass and yield accumulation in advanced sugarcane crops in the Australian tropics. The postulated alternative causes of the slowdown were (i) lodging in large crops induced when the crop biomass exceeded that able to be physically supported under prevailing environmental conditions; (ii) natural, age-induced reductions in key attributes of growth in older crops, and (iii) seasonal changes into environmental conditions (perhaps temperature, humidity or insolation) that are less favourable to growth.

In all, four field trials were successfully conducted, variously sampling differences in variety, year and/or site. Three of the successful trials sampled rainfed sites in the wet tropics, and one, an irrigated site in the dry tropics.

Despite the diversity of conditions sampled in these four field studies, there was a considerable degree of consistency in the responses to the imposed treatments, enabling some generalised inferences to be drawn on the constraints to sugarcane productivity in tropical Australia. At the same time, as will become clearer below, there were some apparent inconsistencies between the field studies reported in Chapters 3 and 4, and the previous work of others (discussed in detail in Chapter 2) that had in large part stimulated the present work.

In this chapter, the generalised conclusions to be drawn from the four field studies are summarised, and some of the differences with the earlier fieldwork are considered in the context of identifying ways to possibly reconcile the inconsistencies. It was considered important that these inconsistencies be resolved as a basis for allowing wider inferences to be drawn on future needs in sugarcane improvement research and development.

5.2 Lodging and yield accumulation

The data obtained in the field experimentation clearly indicated that lodging had a significant negative impact on cane yield and CCS. This effect of lodging was broadly consistent across the seasons and experiments, irrespective of the genotype, crop size and the environment. Prevention of lodging through the use of scaffolding increased cane yield by 11 - 15 %, CCS by 3 - 12 % and sugar yield by 15 - 35 % at the final harvest in August/September. The effects of lodging on CCS were greatest immediately after lodging, while effects on cane and sugar yield were present and sustained throughout the growth period after lodging. The yield reductions following lodging were mainly the result of lower cane biomass (7 - 16%) and lower sugar content (2 - 8%) of the live stalks and a reduction (6 - 10%) in the number of live stalks. In the control treatment, there were additional dilution effects of 0.3 - 0.7 units from the lower CCS of dead and rat-damaged cane, resulting in further reductions in sugar yield.

Compared with the scaffolding treatment, there was a reduction in the sugar content of the live stalks in the control treatment shortly after lodging. This immediate effect of lodging on the sugar content of the live stalks could be related to the mobilisation of the stored sucrose towards those growth processes involved in overcoming the disruption to the crop canopy caused by the lodging event. Apart from stalk damage and breakage, plants had reduced apical dominance after lodging, allowing side shooting (Plate 5.1) in the control treatment, particularly in 1998/99 at Feluga where subsequent lodging events took place. In the control treatment, it might be expected that sucrose reserves were broken down to re-initiate stalk growth (e.g. re-gain upright posture or canopy redevelopment) resulting in live stalk CCS reductions. This is in accordance with the findings of Parthasarathy and Narasimha Rao (1953) and Narasimha Rao (1958) under artificially lodged conditions for sugarcane in pot experiments. In these experiments, they attributed a loss of about 1.8 units of sucrose content after lodging to an increase in the content of reducing sugars and a reduction in purity coefficient of lodged cane. Borden (1942) observed similar results, i.e., reductions up to 1.8 units in sugar content of an artificially lodged cane in a pot experiment. However, these losses in sugar content could be variable depending upon the extent of lodging, i.e., degree of inclination from the vertical and the amount of mutual smothering of stalks and leaves. There is evidence of increased sugar losses with the increase in extent of lodging (Parthasarathy and Narasimha Rao, 1953; Narasimha Rao, 1958).

In the present studies, dilution effects from dead and rat-damaged cane resulted in further reductions (0.4 - 0.7 units) in sugar content of the final harvested crop compared with effects due to live stalk CCS decreases alone. The sugar content of the dead cane was less than half that of sound live cane. Hughes and Muchow (2000) reported similar dilution effects from the low sugar content of dead cane.

Depending on the timing/nature/extent and frequency of lodging events, different amounts of stalk death were observed in the control treatments in the present studies. A considerable amount of rat-damage was experienced in the wet tropics, amounting to up to 8.8% of the total fresh cane at the final harvest particularly during 1998/99. This damage occurred only in the control treatment after lodging. The losses from lodging in the current studies might be conservative since only small amounts of stalk death (0.6 - 0.9 stalk m^{-2}) were observed compared to some previous studies where it was 2 to 3 stalk m^{-2} (Muchow *et al.*, 1994a and 1995). The differences in the amount of stalk death could be attributed to differences in the timing/type/intensity or frequency of lodging events. In the current studies, very uniform and uni-directional lodging events were experienced that resulted in 100% stalk lodging in the control treatments.

Plate 5.1 Side shooting of main stem in the control treatment after lodging at Feluga in 1998/99.

Muchow *et al.* (1994a and 1995) argued that stalk loss from deterioration after lodging was a major contributing factor to the observed 'yield plateau' in large sugarcane crops. However, no net loss of whole stalks, as was reported by Muchow *et al.* (1995), was detected in any of the three trials here where lodging was experienced, not even in the wet tropical environments where the most rapid decomposition of stalks might be expected. Based on these observations, it is unlikely that dead stalks could decompose or in some other way disappear completely during the course of an experiment (about 4 to 5 months) in any environment. It is therefore suggested that the stalk losses reported by Muchow *et al.* (1995) may have been due to spatial field variations in stalk numbers between the sampling areas or alternatively, through the overlooking of some dead stalks during sampling late in the season when the crop was large and lodged. In the present study, initial stalk counts were taken in all subsequently sampled quadrats before lodging and this eliminated the possibility of any spatial variation contributing to changes in stalk numbers.

The field results strongly supported the hypothesis that the disruption of the canopy architecture caused by lodging affected light interception and ultimately reduced radiation use efficiency. The 3 - 16% lower biomass (total or millable cane) of the live stalks in the control treatment after lodging, relative to the scaffolding treatment, was attributable to both the reduction in radiation interception and the lower RUE of the lodged crop.

While there has been little research on lodging in sugarcane, Setter *et al.* (1997) reported that in lodged rice, the substantial reduction in canopy photosynthesis was associated with more radiation becoming intercepted in the top part of the canopy. In this case, the canopy effectively became 'thinner' and less efficient through greater shading of lower leaves and there was an overall reduction of 60 – 80% in canopy photosynthesis. This effect is equivalent to a reduction in RUE, and quite likely occurred immediately after lodging in the sugarcane when only the top layer of leaves was intercepting almost all of the radiation.

In addition to the disruption of the crop canopies, there was an increase in leaf senescence associated with a reduction in the green leaf area per stalk and ultimately in the crop LAI. This lowered the light interception by up to about 10% in the control compared to the scaffolding treatments. All these factors in combination reduced the whole canopy photosynthesis and the RUE of the control treatments. There are several reports from other crops where the occurrences of lodging events are known to reduce the radiation interception and RUE of the crops. Weibel and Pendleton (1964) and Larson and Maranville (1977) attributed reductions in the grain test weight and total biomass of wheat and sorghum crops to the decreased light interception by lodged crops. Similarly, Hitaka (1968) reported that self-shading of leaves and panicles due to lodging reduced the light interception and canopy photosynthesis in rice crops.

The conclusions from the current studies are also consistent with the observations of an artificially lodged field experiment, where lodging reduced the weight and sugar content of the live stalks, with additional stalk damage resulting in about 16 - 25% reductions in sugar yield (Vaidyanathan, 1954). There are several other reports of comparisons between lodged and non-lodged cane drawn from various parts of the fields (e.g. Agnihotri, 1965; Sharma and Rao, 1978; Sharma and Sharma, 1979; Sayed *et al.*, 1980; Ahmad, 1997). In these studies, it was argued that in addition to reducing the sugar content and the weight of the stalks, stalk breakage as a result of lodging also rendered the crops more susceptible to disease and pest infestations. Further, lodging resulted in an increase in the content of reducing sugars with reductions in juice purity and sugar recovery. Field experiments with other crops have also shown that lodging is a clear constraint to yield potential under high yielding conditions (e.g. soybeans: Cooper (1971); wheat: Weibel and Pendleton (1964); Fisher and Stapper (1987); Hay and Walker (1989); Stapper and Fisher (1990); sorghum: Larson and Maranville (1977); maize: Carter and Hudelson (1988)).

In sugarcane, it is likely that direct losses to growers as a result of lodging, in terms of cane and sugar yield, may vary with the timing and extent of lodging and the size of the crop. Indirect losses, such as extra harvesting costs and extraneous matter (EM) effects on CCS and millings costs, can also be substantial (Crook *et al.*, 1999; Kent *et al.*, 1999). In mechanically harvested lodged cane, from the increased amount of tops in cane supply, it was estimated that the EM content of lodged crops would be about 4% higher than non-lodged crops (Jackson *et al.*, 2000). The economic losses due to lodging were much greater when these additional effects of lodging were taken into account (Singh *et al.*, 2000 – see Appendix III.2). Further, stool damage during the harvesting of lodged crops may also reduce the yield potential of the subsequent ratoon crops. All these losses would likely be variable depending on extent and frequency of lodging events.

5.3 Crop age and seasonal factors and yield accumulation

The results of the field studies did not support the hypothesis that crop age and/or changing seasonal factors were limiting productivity, at least for 12 - 15 month crop cycles in tropical environments of Australia.

There was no evidence that crop age had any impact on crop growth rate up to the time of the final harvests. At both the Ayr and Feluga sites, for almost every growth variable, the growth of the scaffolded (older) crop treatment was similar to that of the late (young) crop treatment. Both of these treatments continued to accumulate biomass until the final harvests in August/September. If crop age were a significant factor affecting crop growth rate, then different rates of growth would be expected between these two treatments. The lack of an age effect is consistent with other studies (Das, 1936; Borden, 1945 and 1948; Evensen *et al.*, 1997), where the crops continued to accumulate cane and sucrose yields beyond 18 months of age as long as they did not flower. It should be noted, however, that the current studies were all terminated before the absolute end of the normal commercial harvesting period (November/early December) in Australia. The possibility of an aging effect on crop growth rate in older crops, such as late harvested or two-year-old crops, therefore cannot be discounted on the basis of the current research.

Similarly, there was no evidence that seasonal factors were implicated in any slowdown of growth in any of the trials. At all sites, both the scaffolding and late crop treatments continued to accumulate biomass until the final harvests in August/September. One concern was the slowdown in growth, and associated decline in RUE, before the final harvest in these treatments at Ayr. The analysis of the observed responses using a crop growth simulation model supported the suggestion that in this study, the crop growth rate was reduced by water stress in the last 6 - 7 weeks. When irrigation was applied in the simulation to eliminate water stress, the negative effect on RUE was removed. Accepting that interpretation for the growth slowdown in the Ayr study, then there was no indication of a slowdown in crop growth rate at any site in the current studies, where scaffolding was used to prevent lodging. It should be noted that in the current studies, the observed mean temperatures during the winter months remained well above the minimum threshold value of 8 - 10°C reported for sugarcane growth under South African (Inman-Bamber, 1994) and Australian conditions (Robertson *et al*, 1998). Thus direct effects of lower temperature (e.g. mean temperature <15°C) on crop growth could not be ruled out in other environments and seasons. Likewise, the effects of other seasonal changes outside the range of those sampled here cannot be absolutely discounted.

5.4 Inconsistencies between the current and previous studies

The present studies provide strong empirical evidence to support the earlier hypothesis raised by Muchow *et al.* (1995) to explain the results of field studies in tropical Australia, that lodging may be a serious constraint to the productivity of advanced sugarcane crops. The results clearly implicate 'lodging' as a major constraint to high yields, even in the moderately yielding crops of the wet tropics. In addition to causing stalk death, lodging also affected biomass accumulation and sugar concentration in the live stalks. The economic losses due to lodging were even greater when the dilution effects from EM, as a consequence of the mechanical harvesting of lodged cane, were taken into account. In farm fields, lodging is commonly more severe than observed in the current studies so losses could be much greater than measured here.

Even so, there remain some important inconsistencies between the current research and the previous studies. Most importantly, in contrast to the earlier research, there was no evidence of a 'yield plateau' or of any physical stalk loss due to deterioration in the current studies. In the previous studies, it was argued that the major effect of lodging on biomass accumulation was the death of stalks and the occurrence of the 'yield plateau' was mainly a result of stalk loss (2 to 3 stalk m^{-2}) due to lodging.

To some extent, the differences between the current and previous studies might be attributed to differences in the extent or nature and/or number of lodging events. But the absence of any 'stalk loss' and the lack of any evidence of a 'yield plateau' in the current studies remain perplexing. Based on the current studies, it seems most unlikely that dead stalks could decompose or in some other way disappear completely during the course of an experiment in any environment. Apart from some level of stalk death, there might have been factors such as spatial stalk variations and/or N stress and/or water stress and/or low temperature that also contributed towards the observed 'yield plateau' in the earlier studies.

Whatever, the possibility that the earlier studies may have encountered sufficiently different seasonal conditions to those encountered here to cause the apparent differences in response, warrants further consideration to exclude the possibility that factors other than lodging *per se* might have been involved in those studies. As demonstrated in the previous chapters, use of physiological frameworks or crop simulation modelling are two approaches well suited to such an exercise. In the later case, it is imperative to incorporate information on lodging generated in the current studies into the model before it can be used to analyse other studies, i.e., 'SUGARBAG' data sets where lodging was experienced. But this process of incorporating information on lodging into the model is still under consideration. The next chapter presents a comprehensive re-analysis of the data from the Muchow *et al.* (1995) studies by using frameworks presented earlier in this thesis (Chapter 2) to help differentiate the confounding effects of various factors on crop growth.

Chapter 6 Re-analysis of previous data to evaluate alternative causes of the 'yield plateau'

6.1 *Introduction*

As noted in the preceding chapter, the current studies provided quantitative evidence to support the earlier hypothesis raised by Muchow *et al.* (1995) that lodging may be a serious constraint to the productivity of sugarcane in tropical environments of Australia. However, there were some apparent inconsistencies between the current studies reported in Chapters 3 and 4, and the previous studies of Muchow *et al.* (1995).

In the current studies, observations of the growth of lodged control plots suggested that without pre-marked sample quadrats, it was impossible to do stalk counts and accurately define the harvest areas in the lodged crops. Other observations from the current studies suggested that initial high numbers of stalks in sugarcane plant crops usually stabilised to ~ 8 stalk m^{-2} at about 6 to 8 months after planting, corresponding well with the earlier findings of Garside and Nable (1996). The current studies also suggested that it was unlikely that lodging would result in any stalk loss through rotting and deterioration, even in the humid environments of the wet tropics.

To some extent, the discrepancies between the current and previous studies might be attributed to the nature and/or frequency of lodging events. Even so, the apparent physical loss of some of the stalks and the presence of a 'yield plateau' in the previous studies would remain unexplained. In the earlier studies, the trash (dead leaf and dead cabbage) components were not fully recovered, resulting in an under-estimation of crop biomass by about 15% (Evensen *et al.*, 1997). Even so, this under-estimation of the trash component would explain only part of the slowdown, and would not have accounted for the plateau in yield accumulation.

Given these discrepancies and inconsistencies, it was hypothesised that apart from some level of stalk death due to lodging and the direct impact of lodging on crop growth, there might have been other factors that contributed towards the observed 'yield plateau' in the earlier studies. The possible explanations behind the 'stalk loss' and 'yield plateau' are:

1. The stalk loss was a confounded effect of spatial stalk variations that contributed to the apparent change in stalk numbers;

2. Potential crop growth rate was reduced by the occurrence of some level of N and/or water stress; and

3. Potential crop growth rate was reduced directly by the influence of other environment conditions (e.g. temperature or insolation).

It was considered a useful strategy to undertake re-analyses of the crop growth data reported in studies that had reported a 'yield plateau', to explore the plausibility or otherwise of these hypotheses. The approach followed was to re-analyse the reported crop, soil and weather data from the earlier studies, incorporating the assumptions inherent in these hypotheses. Depending on the assumptions made, the results of such re-analyses might serve to strengthen or otherwise the interpretations placed on the observed responses in the present study. Through the foresight of previous researchers, detailed data from several earlier studies of sugarcane growth and yield, under a range of conditions in the tropics, were available in a database called 'SUGARBAG'. This database, which includes data from the study of Muchow *et al.* (1995), was established by CSIRO Tropical Agriculture and maintained with support from the CRC for Sustainable Sugar Production (Prestwidge *et al.*, 1994).

This chapter presents a comprehensive re-analysis of the environmental and crop growth data from several 'SUGARBAG' data sets where lodging was experienced. The re-analyses aimed to evaluate the postulated possible causes of the observed 'yield plateau' in the earlier studies. To do this, the re-analyses looked at the growth and development of live stalks and the factors that contributed to stalk dynamics in these crops. The simulations also estimated crop biomass by taking into account the missing trash components, dead cane and any spatial stalk variations, in order to provide a better understanding of various aspects of the yield slowdown in the previous studies that were re-examined.

6.2 Materials and methods

First of all, a preliminary analysis of the 'SUGARBAG' database was performed to identify relevant data for further analyses in order to achieve the above objectives. Version 4.0 of this database contained information about 72 different sugarcane field experiments, conducted in Australia and in some other countries such as South Africa and Hawaii. But only a few studies were conducted under high input conditions of unlimited water and nutrients, where crops were sequentially sampled throughout the growth period, and where information was available on lodging, and on live, dead and total stalk numbers at various stages.

Three data sets, where crops were grown under high input conditions and experienced a 'yield plateau', were selected for further analysis to evaluate alternate causes of the slowdown in yield accumulation. Of these three experiments, two were conducted in tropical environments in Australia, one at Ayr in 1991/92 and the other at Macknade in 1992/93. The third experiment was conducted in Hawaii at Kunia in 1991/93. For convenience, the Australian and the Hawaiian experiments are considered separately.

6.3 Australian experiments

6.3.1 Experimental details

A brief description of the field experiments conducted at Ayr (1991/92) and Macknade (1992/93) is given in Table 6.1. Detailed information about the Ayr experiment was reported by Muchow *et al.* (1994a) and for the Macknade experiment, by Robertson *et al.* (1996). There was only one 'treatment' for the Ayr experiment, where the crop was grown under normal commercial conditions. For the Macknade experiment, there were four different treatments (two crop classes x two varieties), but only the plant crop data were re-analysed.

In both the experiments, crop growth analysis was performed through sequential sample harvesting and partitioning of the aboveground biomass into different components. At Ayr, the crop was sampled from 167 days after planting (DAP, 4 October 1991) to 445 DAP (8 July 1992). In the case of Macknade, the crop was sampled from 91 DAP (22 October 1992) to 455 DAP (21 October 1993), but the final two samples were withdrawn for Q138 due to some sampling issues. This treatment experienced a considerable amount of rat-damage (M. Spillman, CSIRO, personal communication) that was probably due to early lodging of the crop.

Table 6.1 Details of the field experiments used to evaluate alternative causes of the 'yield plateau' of sugarcane grown in tropical environments in Australia.

Experimental details	Ayr (1991/92)	Macknade (1992/93)	
Variety	Q96	Q117	Q138
Crop start	20 April 1991	23 July 1992	23 July 1992
Irrigation	Furrow	Trickle	Trickle
Date of lodging	February 1992	May 1993	February 1993
Final harvest	8 July 1992	21 October 1993	16 August 1993
Reference	Muchow *et al.* (1994a)	Robertson *et al.* (1996)	Robertson *et al.* (1996)

6.3.2 Environmental details

The data for different climatic parameters such as temperature (°C) and solar radiation (MJ m^{-2}), drawn from the 'SUGARBAG' database, were used to calculate weekly averages for temperature (maximum, minimum and mean temperature) and for solar radiation, for the final year of the studies. These data were then compared with the observed temperature and solar radiation conditions during the current study at Ayr in 1999.

6.3.3 Crop growth parameters

The raw data for numbers of live and dead stalks, aboveground biomass production and biomass accumulation of trash components were obtained from the 'SUGARBAG' database. These data were used to re-compute various crop growth parameters by using the physiological frameworks outlined in Chapter 2.

Stalk number

The numbers of different stalk classes that were live and dead stalk were calculated for samples conducted before and after the lodging of the crops. The observed total stalk number was calculated as the sum of the live and the dead stalk numbers for the respective sample harvests.

Total stalk number (observed, per m^2) = Live stalk number (per m^2) + Dead stalk number (per m^2)..........(i)

Further, it was assumed that total stalk numbers remained the same for samples conducted before and after the lodging of the crops (e.g. 8.0 stalk m^{-2} for Q96 at Ayr and 10.0 and 14.5 stalk m^{-2} for Q117 and Q138 crops respectively at Macknade). The new (calculated) total stalk numbers were used to determine the number of stalks that had 'gone missing' after lodging:

Number of missing stalks (per m^2) = Calculated total stalk number (per m^2) – observed total stalk number (per m^2) ....(ii)

Individual stalk biomass

The aboveground biomass accumulation (g m^{-2}) and the live stalk number (per m^2) were used to calculate the individual live stalk biomass (g) over time.

Biomass per live stalk (g) = Total aboveground biomass (g m^{-2}) / Live stalk number (per m^2)..........(iii)

Trash biomass

The total aboveground biomass and trash biomass were used to calculate the fraction of trash components in the aboveground biomass at any harvest conducted before and after the lodging of the crops.

Fraction of trash biomass = Trash biomass (g m^{-2}) / Total aboveground biomass (g m^{-2})..........(iv)

The trash components comprised about 14 - 31% of the total biomass in a 12 to 24 month crop cycle (Evensen *et al.*, 1997). The current studies (Chapter 4) were consistent with these earlier observations.

To re-compute the trash biomass, it was assumed that after lodging, the trash components comprised about 13% of the total biomass and the proportion then increased up to about 15% at the final harvest. This re-computed trash biomass was used to further calculate the individual stalk biomass and total aboveground biomass production under different scenarios, including the assumption that the dead stalks were live and there was no stalk 'loss' after lodging.

Aboveground biomass

The observed data on total aboveground biomass were re-plotted and overlaid with three more data series of estimated aboveground biomass accumulation.

The first assumed that the trash components comprised about 13 - 15% of the total biomass after lodging. The second data series was the same as the first, but with the additional assumption that the 'dead' stalks had continued to grow at the same rate as the live stalks at any sample date. The third data series was again the same as the first, but assumed that the total stalk number after lodging to be same as it was before lodging (i.e. 8.0 and 10.0 – 14.5 stalk m^{-2} for the Ayr and Macknade studies, respectively) and there was no net loss of stalks after lodging.

6.3.4 Results

6.3.4.1 Environmental conditions

At Ayr in 1991/92, weekly mean temperature for April to July of the harvest year was well above 17°C, with weekly minimum temperature of more than 9°C during that period (Fig. 6.1a and b). These conditions were more or less similar to those observed in the current study at Ayr for April to July during the harvest year (Fig. 6.1a and b).

In 1991/92, for the period of January to April, the weekly solar radiation was higher than for the current study at Ayr (Fig. 6.1c). However, for the period of May to July, almost similar levels of solar radiation were observed in both of the studies (Fig. 6.1c).

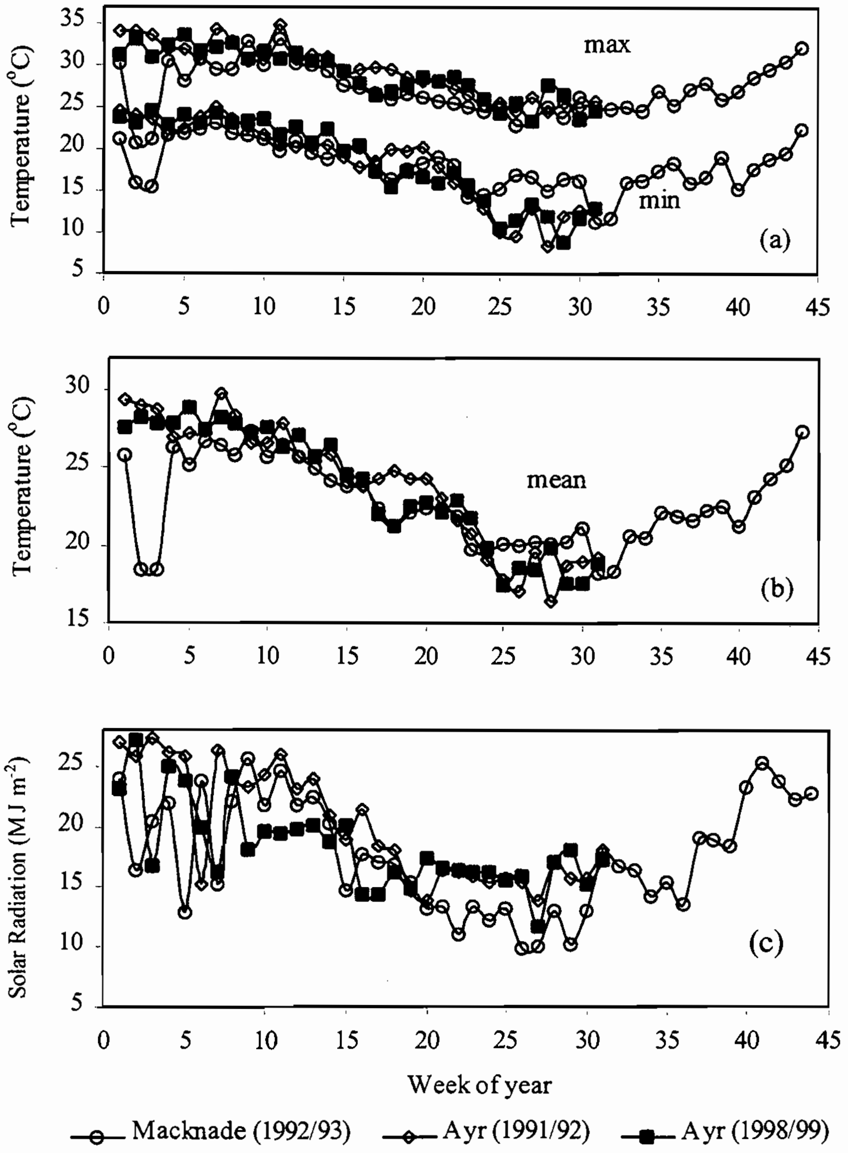

Fig. 6.1 Weather data showing weekly means of (a) daily minimum and maximum temperature, (b) daily mean temperature, and (c) daily solar radiation as observed during the harvest years at Ayr (1991/92 and 1998/99) and at Macknade (1992/93).

In the case of the Macknade 1992/93 study, relative to the Ayr studies, a warmer winter was experienced during the harvest year with average mean temperature well above 20°C (Fig. 6.1a). Compared to the current Ayr study, at Macknade in 1993, solar radiation was periodically lower during the months of April to July (Fig. 6.1c).

At Macknade in 1993, the rainfall was normal and uniformly distributed throughout the growth period (Fig. 6.2). At Ayr in 1992, the rainfall was average but came mainly in three heavy falls (Fig. 6.2).

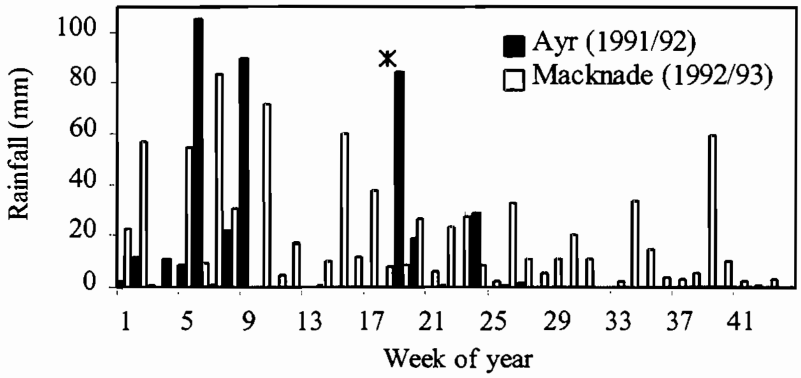

Fig. 6.2 Weekly rainfall observed in the harvest year at Ayr in 1991/92 and at Macknade in 1992/93. The symbol (ж) shows date of the last irrigation at Ayr in 1991/92.

6.3.4.2 Individual stalk growth

Throughout the growth period, there was an ongoing increase in calculated individual stalk biomass accumulation with time in both the Ayr and the Macknade crops (Fig. 6.3).

At Ayr, individual stalk biomass accumulation slowed immediately after lodging in February (Fig. 6.3). However, it later recovered and stalk growth resumed after that time (Fig. 6.3). Similarly, in the Macknade crops, a slight slowdown was observed in stalk biomass accumulation after lodging. Compared with Q117, stalk growth in Q138 slowed later in the season than when lodging occurred in Q117 (Fig. 6.3). This might have been due to another lodging event that occurred in Q138 after the first lodging in February, although there was no observation recorded that might clarify the situation.

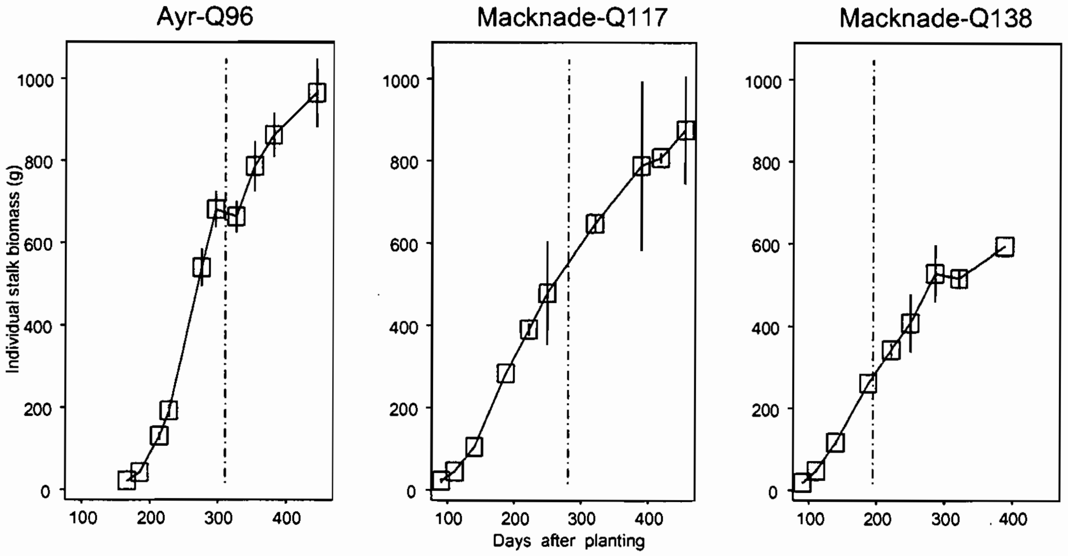

Fig. 6.3 Biomass accumulation per stalk as recorded over time at Ayr in 1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

6.3.4.3 Stalk dynamics

In both the studies, during the active tillering phase, the number of live stalks was very high, i.e., 15 - 20 stalks m^{-2} (Fig. 6.4).

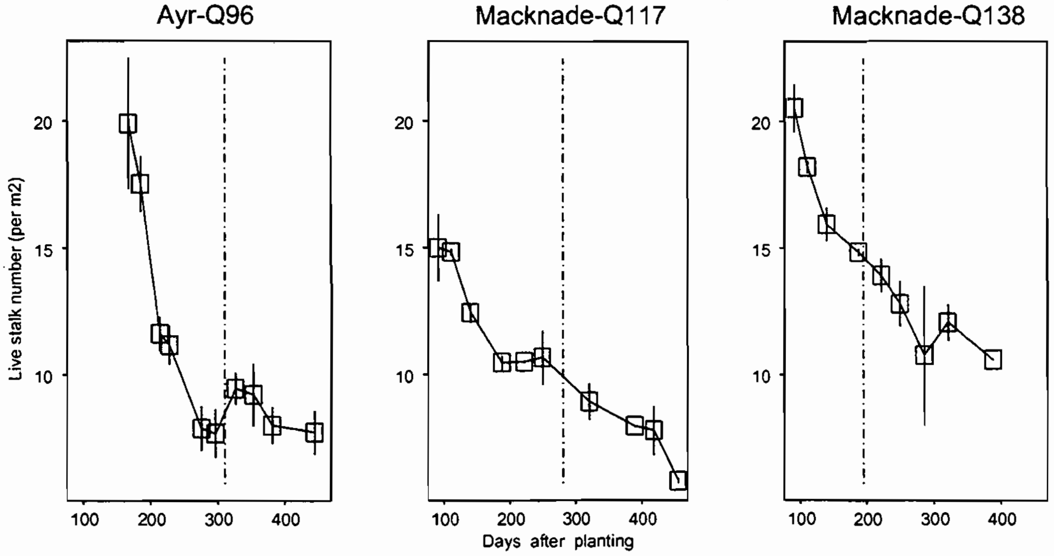

Fig. 6.4 Numbers of stalk (live and sound) recorded at each harvest at Ayr in1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

At Ayr, after the active tillering phase, the number of live stalks declined to 7.7 and 7.9 stalk m^{-2} during January and February respectively (Fig. 6.4). This decline in stalk number occurred well before the lodging of the crop in late February (Fig. 6.4). However, during the post-lodging period of March to April, stalk number again increased at a rate of about 1.5 - 1.7 stalk m^{-2}, resulting in more than 9 stalk m^{-2} (Fig. 6.4). Then later in the season, the stalk numbers again declined to 8.0 and 7.7 stalk m^{-2} at the May and July harvests, respectively (Fig. 6.4). No dead stalks were recorded at any of the samplings at Ayr, even at the later samplings (Fig. 6.5). Meanwhile, standard errors of the numbers of live stalks were sometimes relatively large compared with the differences between the sample means (Fig. 6.4). Taken together, these data can be viewed as consistent with the hypothesis that at Ayr, the variation in stalk number may have been a spatial effect rather than a stalk loss due to lodging.

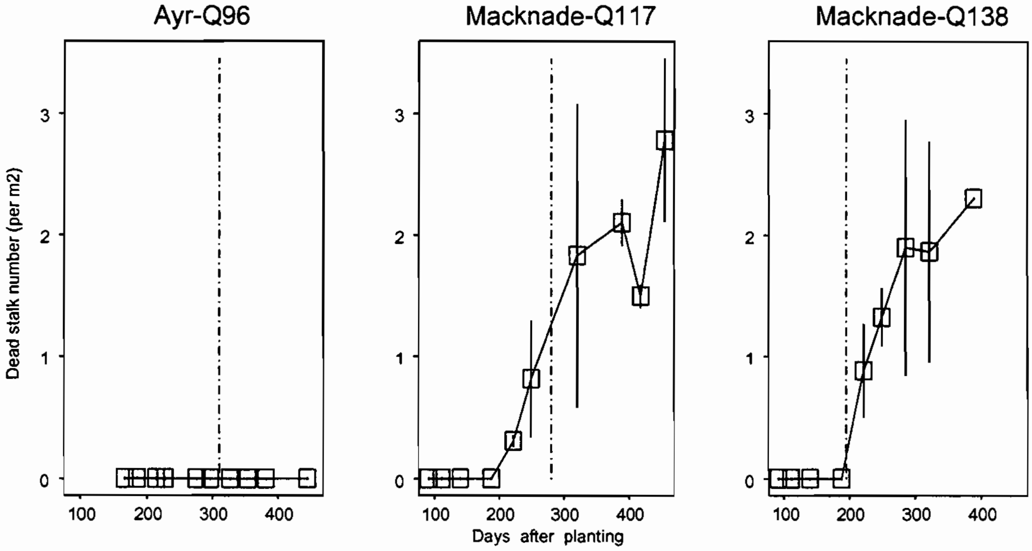

Fig. 6.5 Numbers of dead stalks as recorded at each harvest at Ayr in 1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

More live stalks were observed in the Macknade crops than the Ayr crop (Fig. 6.4). The higher numbers of stalks might have been the result of the fact that the soil on the experimental site was fumigated, since other studies have shown that fumigation enhances initial tiller survival (Muchow *et al.*, 1994; Garside *et al.*, 1999). At Macknade in Q117, the live stalk number stabilised at about 10 stalk m^{-2}, well before the occurrence of lodging (Fig. 6.4). However, in the case of Q138, the number of stalks stabilised after the lodging of the crop (Fig. 6.4). From 250 DAP until the final harvest, the number of live stalks varied up to 3.3 and 4.8 stalk m^{-2} for the Q138 and Q117 crops, respectively. During the same period, the number of dead stalks increased significantly over time, resulting in about 2.5 dead stalk m^{-2} at the final harvest in both the Q117 and Q138 crops (Fig. 6.5). The standard errors of the observations of numbers of dead stalks were very large relative to the differences between sample dates, indicating that the spatial variation was large (Fig. 6.5).

At the final harvest in October, the number of live stalks had declined to less than 6 stalks m^{-2} in Q117 (Fig. 6.4). However, during the post-lodging growth periods, the number of dead stalks did not increase at the same rate as the decline in the number of live stalks, which resulted in a 'loss' of about 1.5 and 3.0 stalks m^{-2} in the Q138 and Q117 crops, respectively (Fig. 6.6). It seems most unlikely that up to 5 m tall 'whole' stalks, each weighing about 3.0 kg fresh weight, might have disappeared completely in a period of 30 to 35 days. Possibly, the spatial variations in stalk number caused this effect, rather than stalk deterioration and loss due to lodging.

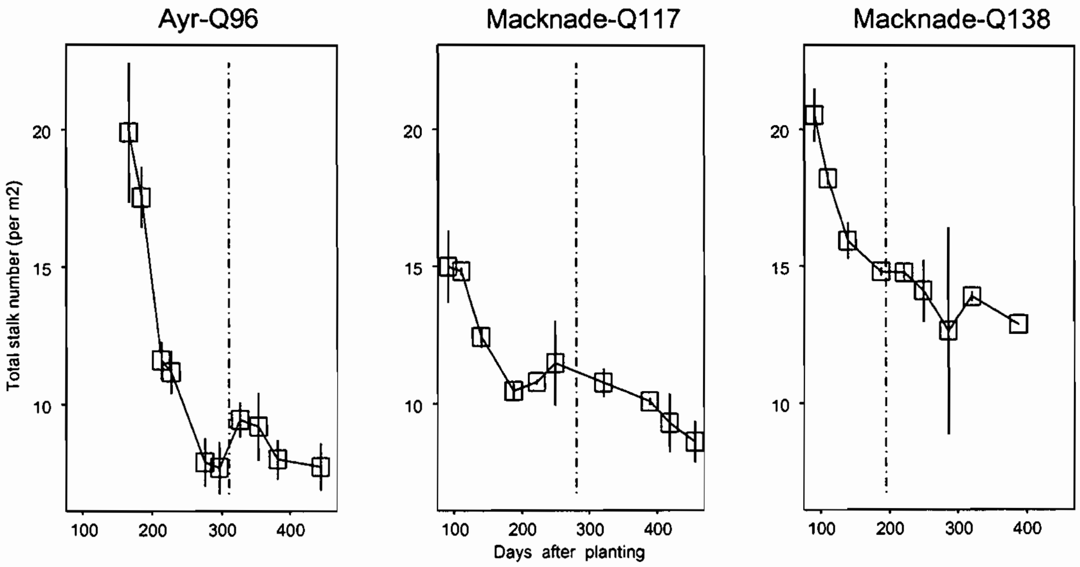

Fig. 6.6 Total number of stalks (live plus dead) recorded at each harvest at Ayr in 1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

6.3.4.4 Trash biomass

In all cases, the reported recovery of trash biomass increased with time up to about 300 DAP (Fig. 6.7). Then it declined during the late season growth period, at both the sites (Fig. 6.7). The maximum reported trash biomass of 500 g m^{-2} at Ayr (for Q96) was less than half of the trash biomass recorded in the current study at Ayr (for Q117). At the final harvests, the reported levels of trash biomass were only 500, 100 and 175 g m^{-2} for the Q96 (Ayr), Q117 (Macknade) and Q138 (Macknade) crops, respectively (Fig. 6.7). The decline in dead trash biomass later in crop growth suggested that the trash biomass might not have been fully recovered in these experiments especially during the late growth periods. Given the sustained wet conditions at Macknade (Fig. 6.2), it is likely there was some biomass loss due to deterioration of the dead leaves.

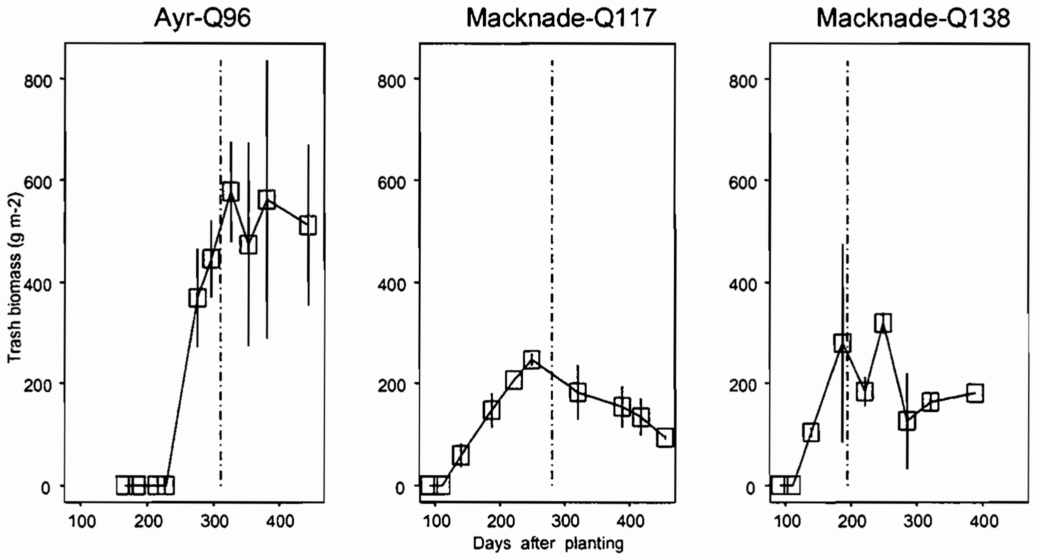

Fig. 6.7 Trash biomass production as reported in the 'SUGARBAG' datasets at Ayr in 1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and dotted lines show the date of lodging.

For both the 'SUGARBAG' experiments, the fraction of trash biomass in the above ground biomass was determined (Fig. 6.8, Table 6.2). At Ayr, for Q96 the trash biomass comprised up to 9% of the aboveground biomass before lodging (February 1992), and then declined later in the season to only 7% at the final harvest in July 1992. Similarly, at Macknade, the trash biomass comprised up to 5 to 7% of the aboveground biomass before lodging and then declined to only 2 to 3% at the final harvest, in both the Q117 and Q138 crops (Fig. 6.8, Table 6.2). These low percentages suggest that in both the experiments, only partial recovery of the trash components contributed towards an under-estimation of the total aboveground biomass.

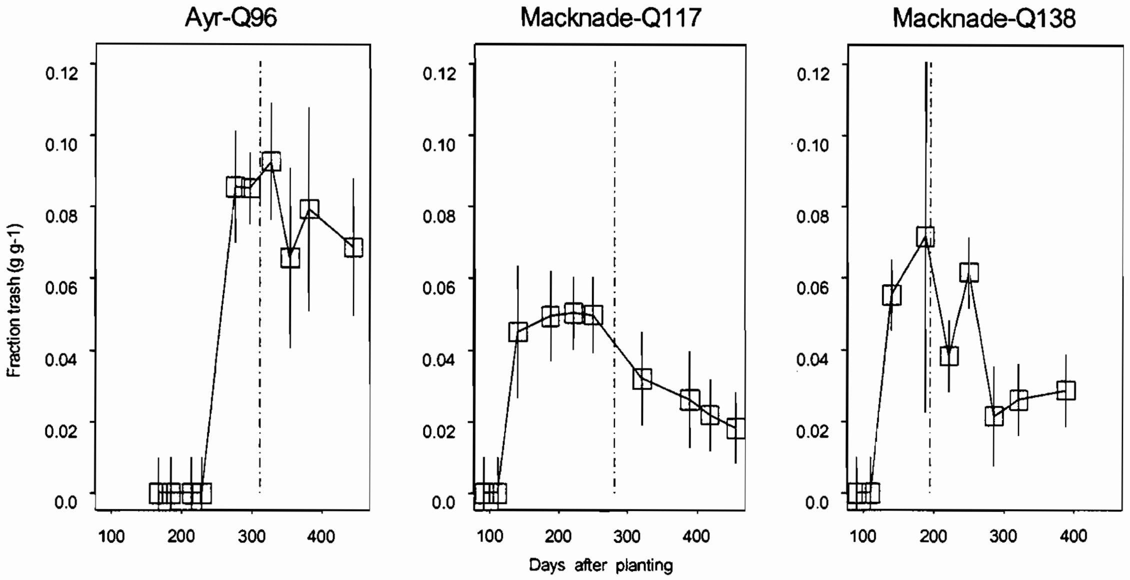

Fig. 6.8 Fraction of biomass in the trash component over time, as recorded in the 'SUGARBAG' data at Ayr in 1991/92 and at Macknade in 1992/93. Bars represent ± SE of the means and dotted lines show the date of lodging.

Table 6.2 Observed fraction of trash components in the above ground biomass at Ayr in 1991/92 and Macknade in 1992/93, as reported in the 'SUGARBAG' datasets.

Harvest number	Ayr (1991/92)	Macknade (1992/93)	
	Q96	Q117	Q138
1	0.00	0.00	0.00
2	0.00	0.00	0.00
3	0.09	0.05	0.06
4	0.09	0.05	0.07
5	0.09*	0.05	0.04*
6	0.07*	0.05	0.06*
7	0.08*	**	0.02*
8	0.07*	0.03*	0.03*
9	**	0.03*	**
10	**	0.02*	**
11	**	0.02*	**

* - Sampled after lodging

** - Not measured

As noted earlier, the data of Evensen *et al.* (1997) and from the current studies (Chapters 3 and 4) suggested that under normal circumstances, in 12 to 15 month crop cycles, the trash biomass constitutes about 14 - 20 % of the aboveground biomass. Given that, it is likely that the trash biomass was under-estimated by about 60 to 90% in the Ayr (1991/92, Q96) and the Macknade (1992/93, Q117 and Q138) experiments. On the basis of the observed values of 6000 to 7000 g m^{-2} of aboveground biomass, this would translate into an under-estimate of the biomass production in the Ayr and the Macknade crops (Fig. 6.9), of about 9% and 15%, respectively. These values are similar to the re-analyses calculated for these experiments by Evensen *et al.* (1997).

6.3.4.5 Aboveground biomass

The aboveground biomass accumulation followed a sigmoidal pattern with time in both the Ayr and Macknade crops (Fig. 6.9). At Macknade, shortly after lodging, the aboveground biomass production slowed in cultivars Q117 and Q138. In contrast, after lodging, the Ayr crop initially continued to accumulate biomass at similar rate to that before the lodging (Fig. 6.9).

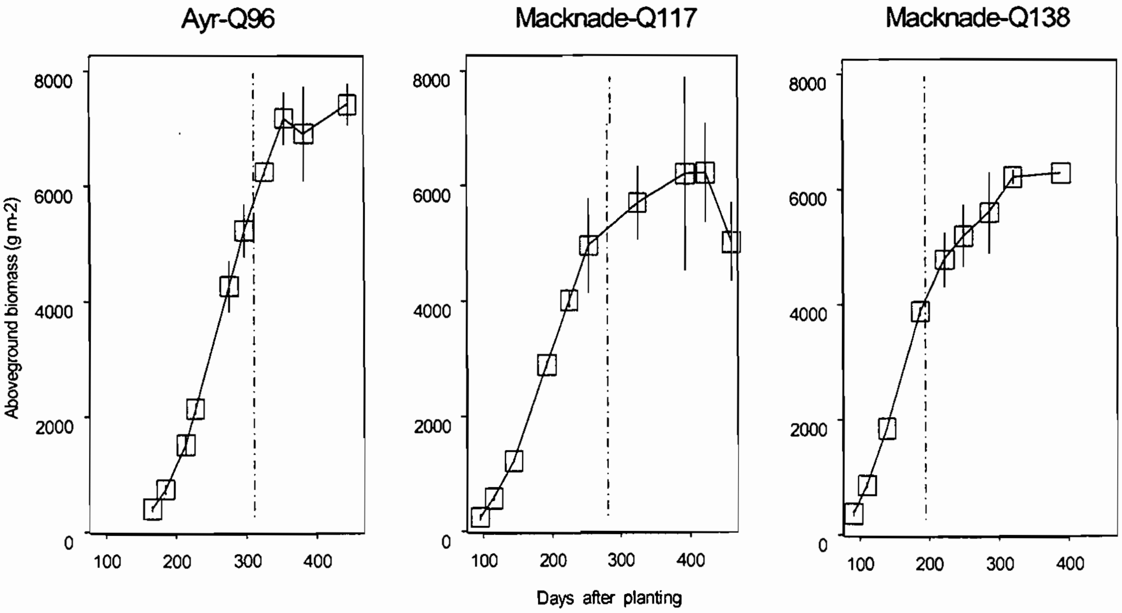

Fig. 6.9 Total aboveground biomass accumulation as measured in tropical Australian environments at Ayr (1991/92) and at Macknade (1992/93). Bars represent ± SE of the means and dotted lines show the date of lodging. Data are as reported in 'SUGARBAG'.

It is possible that the impact of lodging on biomass accumulation was masked by the apparent increase in stalk number after lodging, which as noted above, might have been due to the spatial stalk variations and/or sampling error associated with the intermingling of stalks after lodging (Fig. 6.4). Both the Ayr (Q96) and Macknade (Q138) crops experienced late season plateaus in biomass production. However, in the case of cultivar Q117 at Macknade, biomass production had declined by more than 20% at the final harvest in October (Fig. 6.9). In each case, the late season 'yield plateau' was attributed by the original experimenters mainly to lodging-induced stalk death and loss (Muchow *et al.*, 1994a; Robertson *et al.*, 1996).

At Ayr, the re-estimation of the trash components, on the assumption that the trash components comprised about 13 – 15% of the total biomass after lodging (section 6.3.3 above), changed the apparent 'plateau' to a slowdown in yield accumulation, with the final total biomass being estimated at about 8100 g m^{-2} (Fig. 6.10). That is, the aboveground biomass production was increased by up to 9% when the trash components that were assumed not recovered in the study were taken into account.

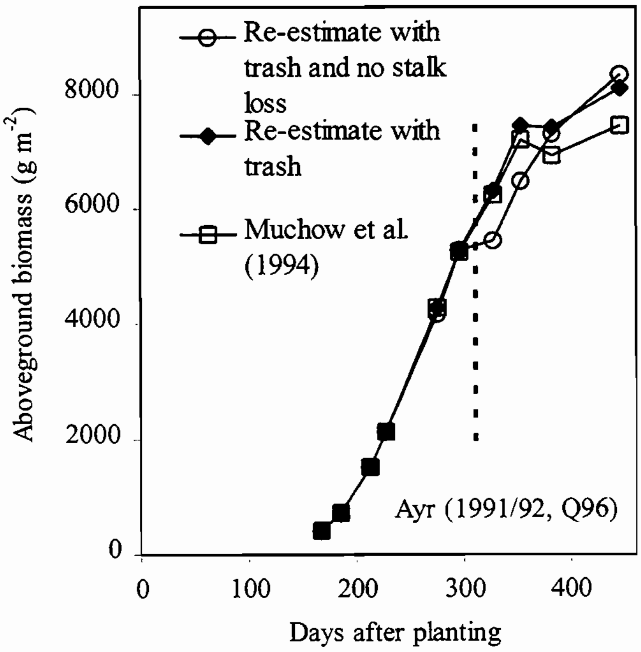

Fig. 6.10 Comparison of the observed data and two re-computed series, for aboveground biomass accumulation for Q96 at Ayr in 1991/92. Original data from Muchow *et al.* (1994a) as recorded in 'SUGARBAG'. Dotted line shows the date of lodging.

Consistent with the observation (Fig. 6.5) that no dead stalks were recorded in the Ayr 1991/92 study, the second re-estimation of biomass (Fig. 6.10) assumed the total stalk number after lodging to be same as it was before the lodging (i.e. 8 stalk m^{-2}). This re-estimation eliminated the late season slowdown and/or 'plateau' in yield accumulation, with the final total biomass being estimated at about 8300 g m^{-2} (Fig. 6.10). However, it suggested that there might have been an immediate effect of lodging, i.e., a slowdown in biomass accumulation that was not obvious from the observed data (Fig. 6.10). These re-analyses suggested that at Ayr, the 'yield plateau' may have been an artefact due to the combined effects of the apparent decrease in stalk number due to spatial variations and only partial recovery of trash biomass in the late growth period after lodging.

Similarly, the re-estimation of the trash component delayed the onset of the yield 'plateau' in the Macknade crops, with the total biomass for both cultivars being estimated at about 7100 g m^{-2} (Fig. 6.11a and b). The estimated aboveground biomass production was increased by 15% when the trash components that were presumed not recovered in the studies were taken into account. The estimation of biomass assuming that all the dead stalks were actually alive, eliminated the 'yield plateau' in Q138, and in Q117, further delayed it to the third-last harvest. The estimate of final total biomass was about 8800 g m^{-2} in both the crops (Fig. 6.11a and b). These re-analyses suggested that in these crops, maximum biomass accumulation would have been increased by about 22 to 24%, if the stalk death had not taken place.

Finally, the re-estimation of aboveground biomass assuming that the total stalk number after lodging was same as it was before the lodging, eliminated the 'yield plateau' completely, with the final total biomass being estimated at about 10000 g m^{-2}, for both the Q117 and Q138 crops (Fig. 6.11a and b). The re-analysed data still reflected the immediate effects of lodging, i.e., the slowdown in biomass accumulation, that were present in the observed data (Fig. 6.11a and b).

On the basis of these re-analyses, it is possible to conclude that in the Macknade crops, three different factors viz. an under-estimation of trash biomass, stalk death and the change in stalk numbers over time, all may have contributed to the reported late season 'yield plateau'.

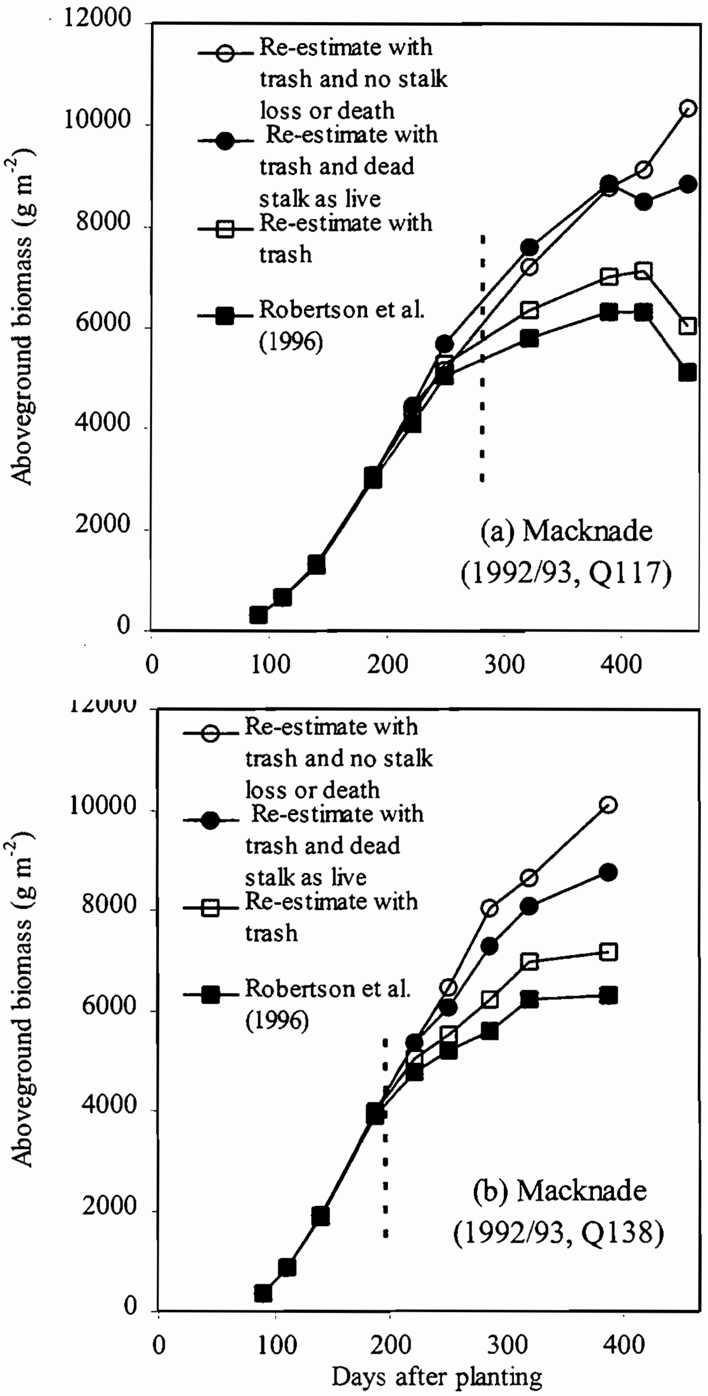

Fig. 6.11 From the data of Robertson *et al.* (1996), observed and three re-computed series for the aboveground biomass accumulation with time at Macknade in 1992/93 for (a) Q117, and (b) Q138. Dotted lines show the date of lodging.

6.4 Hawaiian experiment

6.4.1 Experimental details

A brief description of the field experiment conducted at Kunia (1991/93) is given in Table 6.3. The detailed information about this experiment was reported by Evensen *et al.* (1997).

Table 6.3 Details of the field experiment used to evaluate alternative causes of the 'yield plateau' at Kunia in Hawaii.

Experimental details	Kunia (1991/93)	
Variety	H73-6110	H78-7234
Crop start	21 January 1991	21 January 1991
Irrigation	Drip	Drip
Date of lodging	11 September 1992	11 September 1992
Final harvest	24 January 1993	24 January 1993
Reference	Evensen *et al.* (1997)	Evensen *et al.* (1997)

In this experiment, two cultivars were grown under drip irrigation in a paired-row planting system. The crops were sequentially sampled at 63, 120, 184, 240, 366, 544, and 733 DAP for biomass accumulation and partitioning determinations.

The environmental data relevant to this experiment were analysed as described earlier for the Australian experiments. The crop growth parameters were also analysed similarly to the Australian experiments, the only exception being that the trash biomass was not re-computed, because it was fully recovered in this experiment (Evensen *et al.*, 1997).

The total stalk numbers that were used for individual stalk and total biomass determination purposes were comprised of live primary and secondary stalks, as no dead stalks were recorded in this study.

6.4.2 Results

6.4.2.1 Environmental conditions

At Kunia in 1991/93, throughout the crop growth period, weekly mean, minimum and maximum temperatures were well above 20, 15 and 25 °C respectively (Fig. 6.12a). These temperature levels were much higher than the temperature levels that were observed in the current study at Ayr (Fig. 6.1a and b). The weekly solar radiation was in the range of 13 – 25 MJ m^{-2} throughout the crop cycle at Kunia in 1991/93 (Fig. 6.12b). This was slightly lower than for the current study at Ayr (1998/99) but was almost similar to that of Macknade in 1992/93 (Fig. 6.1c). The rainfall at Kunia came in heavy falls (Fig. 6.12b).

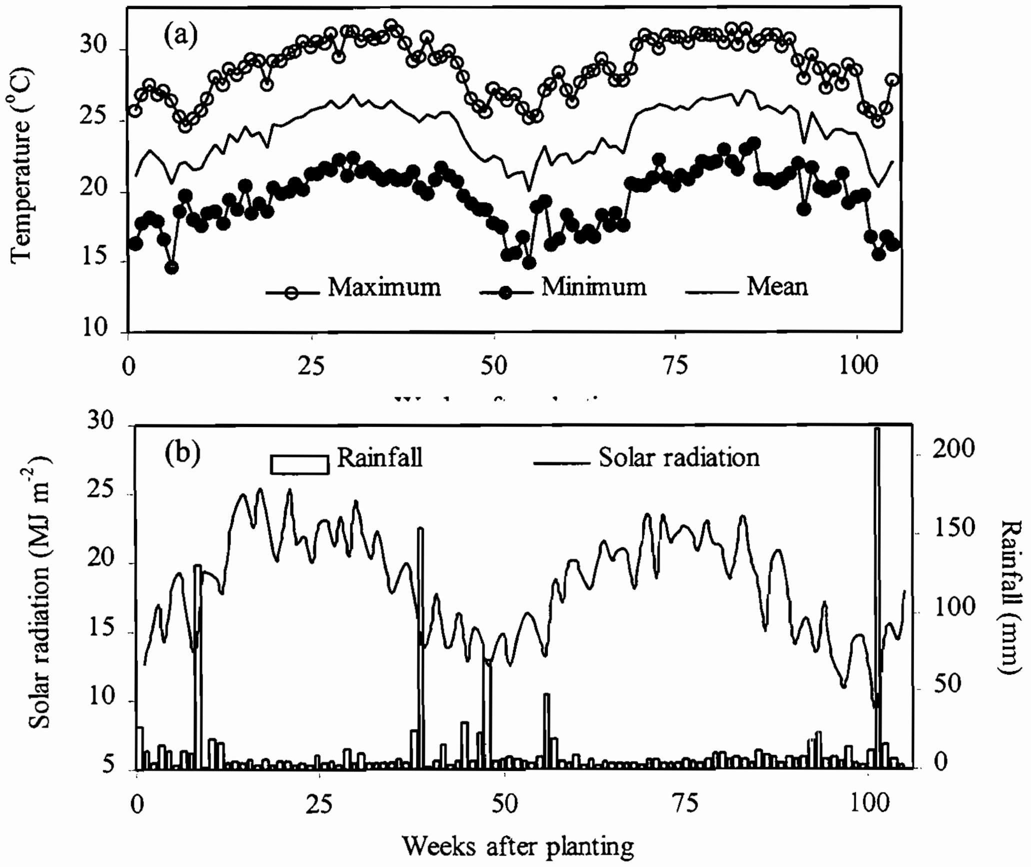

Fig. 6.12 Weather data showing weekly means of (a) daily minimum, maximum and mean temperature, (b) daily solar radiation and sum of rainfall as observed at Kunia, Hawaii (1991/93).

6.4.2.2 Crop growth

Individual stalk biomass

In both the cultivars evaluated, the biomass accumulation of individual stalks increased significantly over time, up to the final harvest at 733 DAP (Fig. 6.13). At about 300 DAP, in both the cultivars, stalk growth slowed slightly but later recovered (Fig. 6.13). However, in cultivar H78-7234, a slight slowdown was again observed in stalk growth shortly after lodging at about 599 DAP (Fig. 6.13).

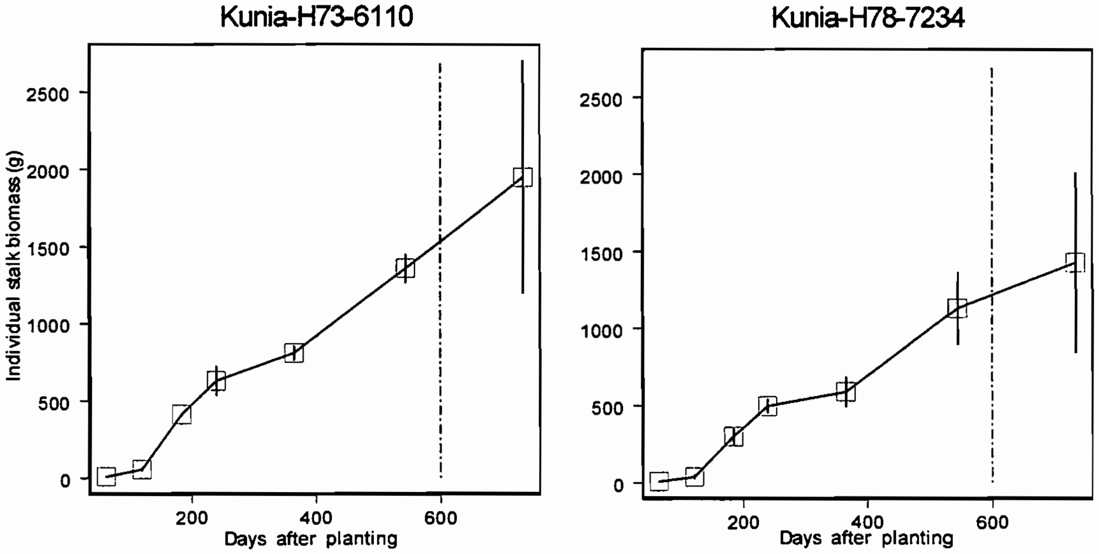

Fig. 6.13 Biomass accumulation per stalk as recorded for two different cultivars, H73-6110 and H78-7234, at Kunia, Hawaii in 1991/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

Stalk dynamics

During the active tillering phase, the numbers of live stalks increased in both the cultivars up to about 18 stalk m^{-2} at 120 DAP (Fig. 6.14). In both the cultivars, live stalk number stabilised at about 8 – 9 stalk m^{-2} at 184 DAP and then declined over time to 7.4 and 5.7 stalk m^{-2} at 544 DAP in cultivars H78-7234 and H78-6110, respectively (Fig. 6.14). This decline in live stalk number occurred well before the lodging of the crop at 599 DAP (Fig. 6.14). The live stalk number continued to decline at the same rate during the post-lodging period (Fig. 6.14). However, no dead stalks were recorded at any of the sample harvests. Thus, it might be reasonably inferred that the variations in stalk number were a spatial effect rather than due to stalk losses due to lodging.

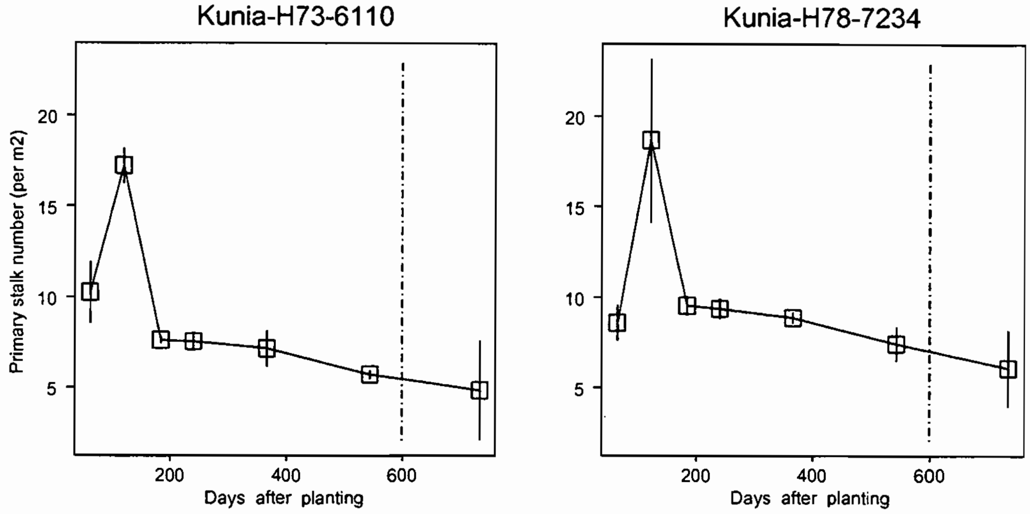

Fig 6.14 Live stalk number recorded at each harvest at Kunia in 1991/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

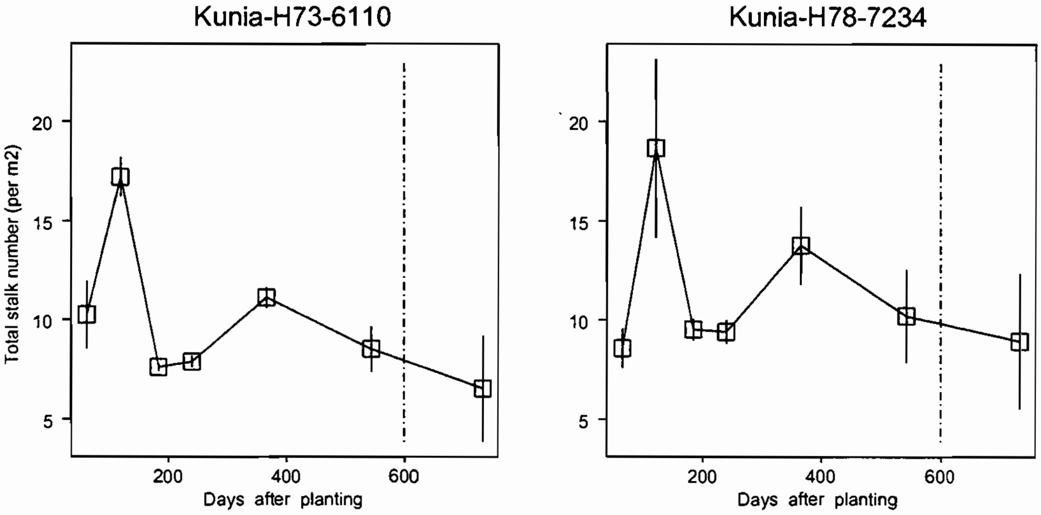

Fig 6.15 Total numbers of stalks (live + sucker) recorded at each harvest at Kunia in 1991/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

During the initial active tillering phase, in both the crops, the total stalk number increased with time up to c. 180 DAP and then declined (Fig. 6.15). Between 200-400 DAP, stalk numbers again increased, mainly as a result of the appearance of secondary (sucker) stalks in both the cultivars (Fig. 6.16). There was a substantial increase in the number of secondary stalks in both the crops at 366 DAP (Fig. 6.16). At the final harvest at 733 DAP, the numbers of secondary stalks were c. 2 and 3 stalk m^{-2} for cultivars H78-7234 and H78-62-110, respectively (Fig. 6.16).

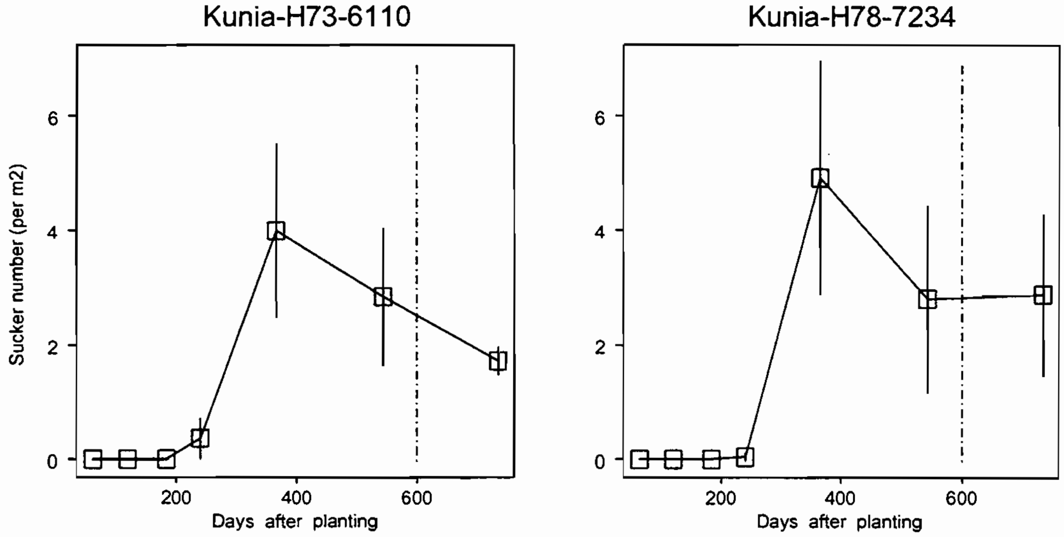

Fig 6.16 Numbers of secondary stalks (suckers) recorded at each harvest at Kunia in 1991/93. Bars represent ± SE of the means and the dotted lines show the date of lodging.

Aboveground biomass

The aboveground biomass in both cultivars at Kunia increased linearly up to about 366 DAP (Fig. 6.17). Thereafter, a slight slowdown was observed in the rate of biomass accumulation in both the crops (Fig. 6.17).

During the late growth period, from 544 to 733 DAP, aboveground biomass declined in both cultivars, although the standard errors were large and the decline was not significant (Fig. 6.17). The highest values of the total aboveground biomass recorded at 544 DAP was 11407 and 11508 g m^{-2}, for cultivars H78-6110 and H78-7234, respectively (Fig. 6.17).

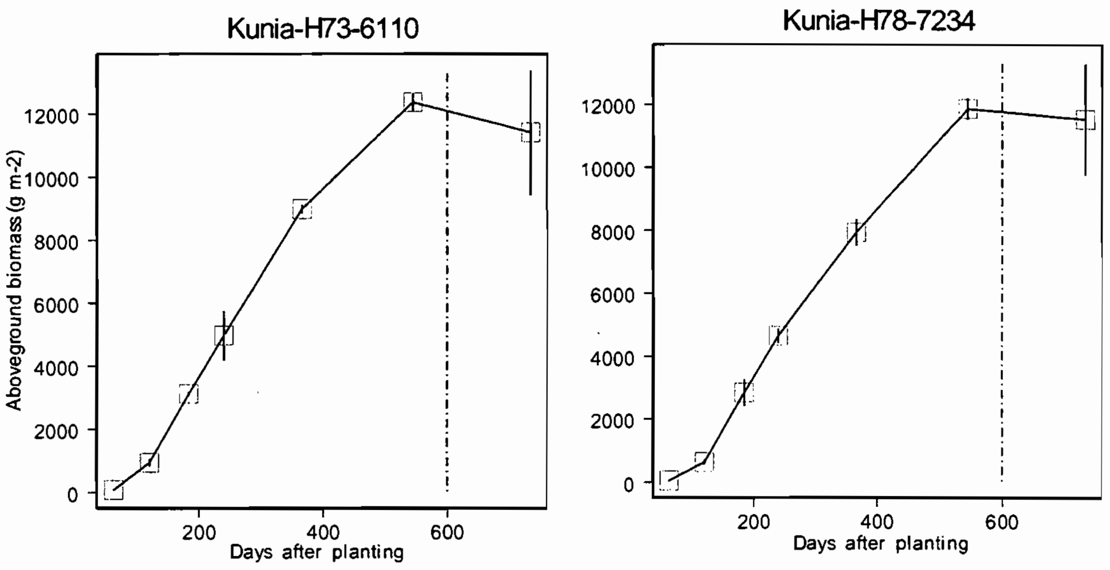

Fig 6.17 Total aboveground biomass accumulation as recorded for two cultivars, H73-6110 and H78-7234, at Kunia in Hawaii in 1991/93. Bars represent ± SE of the means and dotted lines show the date of lodging.

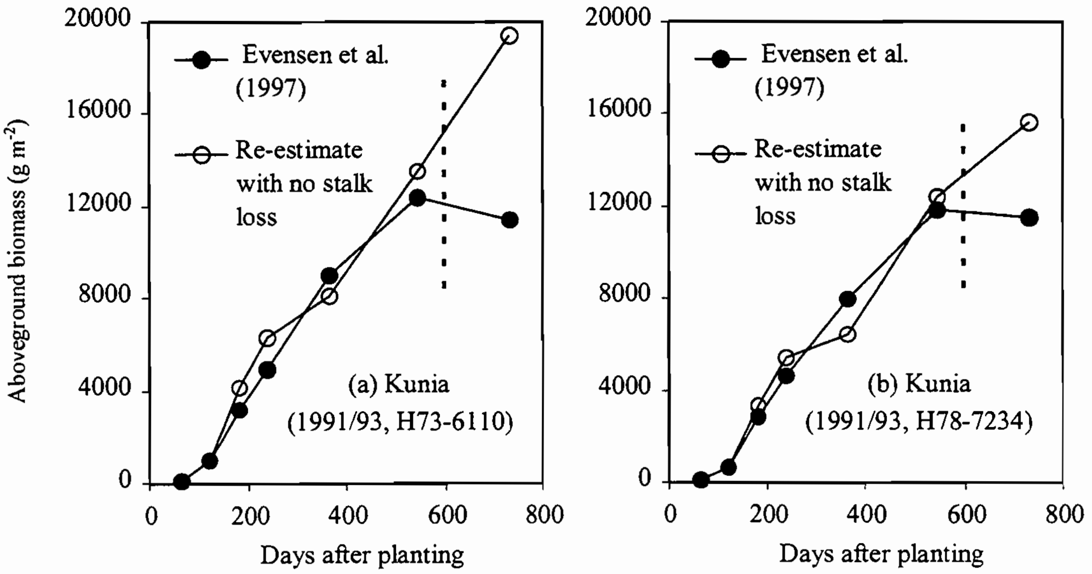

Fig. 6.18 From the data of Evensen *et al.* (1997), observed and re-computed values for the aboveground biomass accumulation with time at Kunia in 1991/93 for (a) H78-6110, and (b) H78-7234. Dotted lines show the date of lodging.

As noted earlier, in both the cultivars, the total number of stalks varied up to 4 stalk m^{-2} over the period from 184 DAP to the final harvest. However, no dead stalks were recorded during this period. The estimation of aboveground biomass, assuming that the total stalk number after lodging was same as it was before the lodging, eliminated the 'yield plateau', with maximum total biomass being estimated at about 19500 and 16000 g m^{-2} for the H78-6110 and H78-7234 crops, respectively (Fig. 6.18a and b). Again, these re-analyses can be interpreted to suggest that variations in estimates of stalk number due to spatial variations, or due to the difficulties of recovering stalks following lodging, may have led to an under-estimation of the total aboveground biomass, resulting in turn in an apparent late season 'yield plateau' or even yield decline in both the cultivars.

6.5 Discussion

The re-analyses of the data indicated that in the previous studies the observed slowdowns in biomass accumulation were invariably associated with declines in stalk numbers. Indeed, when stalk numbers were kept constant after lodging, these effects were removed. In at least two of the situations, there was no evidence of a compensating increase in dead stalks. There is no reliable evidence that dead stalks can rot away in the short time frames available. Thus the evidence for the 'yield plateau'/decline idea hinges precariously on an unexplained 'loss' of stalks. An alternative and very plausible explanation is that once the crops lodge, it becomes difficult to reliably recover all stalks in a sample; and this may also be confounded with some chance variations in stalk numbers (although why these only go one way remains unexplained). It is also likely that due to decomposition of dead leaves, not all trash biomass is recovered after the crop lodges.

The inspection of data revealed that in both the Ayr (1991/92) and the Kunia (1991/93) experiments, the numbers of live stalks varied substantially, by up to 2 and 3 stalk m^{-2}, well before the lodging of the crops. However, in both these experiments, no dead stalks were recorded at any of the sample harvests. Similarly, at Macknade in 1992/93, the rate of loss of live millable stalks exceeded the rates of increase in dead stalks by a factor of approximately two. Muchow *et al.* (1994a) and Robertson *et al.* (1996) attributed this decline in the number of primary stalks to stalk death and subsequent loss through rotting due to crop 'smothering' after lodging. However, they were only able to speculate, because no stalk counts were performed for the future sample areas before the lodging of the crops occurred in their experiments.

The current studies suggested that stalk death as a consequence of lodging reduced the numbers of live stalks by about 6 – 10%. However, there was no physical loss of the dead stalks, even in the humid environments of the wet tropics. In a study at Ayr, Wood *et al.* (unpublished data, 'SUGARBAG' experiment ID 7) observed only small amounts of stalk death, i.e., 0.7 – 1.0 stalk m^{-2}, without any 'net' loss of stalks in Q117 crops that lodged at an early stage. Similarly, in another study at Macknade in 1991/92, no stalk death or loss was recorded in Q117 and Q138 crops that lodged early in the season (Muchow *et al.*, 1993). In light of these experiences, it seems most unlikely that whole stalks as large as 4 - 5m tall and weighing up to 3 kg fresh mass, might have disappeared completely within the period of 30 – 35 days after the crops lodged at Macknade. In the Ayr (1991/92) and the Kunia (1991/93) experiments, the stalk losses occurred well before the lodging of the crops. It may be that the variations in the number of live stalks reported by Muchow *et al.* (1995) were a spatial effect, rather than the result of any stalk losses due to lodging.

The re-analyses of the data provided plausible evidence that, in the Ayr (1991/92) and the Macknade (1992/93) studies, the trash components were under-estimated by about 60 – 90% at the later harvests. The re-estimation of the trash biomass based on other studies, including the current ones, where it was known that trash had been comprehensively sampled, suggested that failure to recover all the trash components could have translated into about 9% and 15% reductions in the aboveground biomass production at the final harvest in the Ayr (1991/92) and the Macknade (1992/93) crops, respectively.

In order to determine the potential contribution of the death of stalks to the 'yield plateau', it was necessary to estimate the likely size of the missing trash components and the effects on growth of the death of some stalks. Unfortunately, the number of dead stalks was recorded only in the Macknade crops. The re-estimation of the aboveground biomass, taking into account the effect on growth of the dead stalks, suggested that the accumulation of biomass would have been increased by about 22 to 24% if stalk death had not taken place in the Macknade crops. Stalk mortality is a common phenomenon in sugarcane cultivation due to the very high tillering capacity of the crops. Shoot numbers tends to maximise around 15 – 20 stalk m^{-2} about 3 months after planting, and then decline to stabilise at around 8 – 10 stalk m^{-2}, about six to ten months after planting (Humbert, 1968; Garside *et al.*, 2000). Other biotic and abiotic factors, including lodging, arrowing and disease/pest damage, can also enhance the rates of stalk death (Martin, 1939; Humbert, 1968). At Macknade in 1992/93, a lot of rat-damage was recorded during the latter half of the season (M. Spillman, CSIRO, personal communication). In addition to lodging, rat-damage might be another factor that accelerated the rate of stalk death in the Macknade crops.

To quantify the possible role of spatial and/or sampling variations in stalk numbers in the observed 'yield plateaus' in the previous studies, it was assumed that the total stalk number did not change after lodging in any of the experiments. When aboveground biomass production was projected after eliminating variations in the number of stalks, there was no evidence of a 'yield plateau' within the experimental time frame. Importantly, the re-analyses of the responses of variety Q96 at Ayr in 1991/92 indicated that the production of biomass may actually have been over-estimated by about 10 – 14% at the March and April samplings (see Fig. 6.10, 300-350 DAP). These re-analyses provide evidence of over-estimates of stalk numbers as a consequence of spatial variations in stalk numbers. In this instance, the over-estimation of biomass at the early stages may thus have led to an apparent rather than real late season 'yield plateau'. Altogether, the re-analyses suggested that for the final harvest at Ayr, the aboveground biomass was under-estimated by about 6% due to chance variations in the number of stalks sampled. Similarly, at the final harvest at Macknade, the aboveground biomass production of the Q117 crop was potentially under-estimated by about 15% as a result of chance variations in the number of stalks (Fig. 6.11a). In the Kunia (1991/93) experiment, the aboveground biomass production could have been reduced by about 40% and 25% at the final harvest in the H78-6110 and H78-7234 crops, respectively, as the result of chance variations in the number of stalks (Fig. 6.18a and b).

The observed values of the average RUE from planting to the final harvest, for the Ayr, Macknade and Kunia crops, respectively were 28%, 40 – 94% and 47 – 60% lower than the potential RUE of healthy sugarcane crops as estimated by Muchow *et al.* (1994a) (Table 6.4). In the absence of any obvious environmental effects that might have reduced RUE, these findings provide further evidence that the biomass production on which they were based may have been under-estimated. Interestingly, the re-calculated values of average RUE, taking account of the putative missing trash components, eliminating spatial variations in stalk numbers, and stalk death where relevant, were similar to that of the potential values of RUE for these crops (Table 6.4).

Table 6.4 The observed and re-estimated values of RUE (g MJ^{-1}) from planting to the final sample harvest for the. Ayr (1991/92), Macknade (1992/93) and Kunia (1991/93) crops. Re-estimates were based on the revised estimates of biomass production taking into account trash losses, changes in stalk numbers and stalk death.

RUE Scenario	Ayr (1991/92)	Macknade (1992/93)		Kunia (1991/93)	
	Q96	Q117	Q138	H78-6110	H78-7234
Potential RUE	1.75	1.75	1.75	1.75	1.75
Radiation intercepted (MJ m^{-2})	5000	5700	5000	11000	9600
Observed RUE	1.37	0.9	1.25	1.03	1.19
With estimated trash	1.60	1.25	1.42	-	-
Dead stalk as live*	-	1.55	1.75	-	-
No stalk loss or death*	1.70	1.75	1.75	1.77	1.67

* - With new fraction of trash components for Ayr and Macknade crops.

Based on the dry weight of the individual live stalks, which increased significantly over time, there was no evidence that any environmental factors were implicated in the slowdown of crop growth up to the final harvests in any of the experiments. The temperature and solar radiation regimes in the previous experiments were more favourable than the temperature and solar radiation levels in the current experiment at Ayr (1998/99), further supporting this assessment. However, in all the experiments, the slight slowdown in the growth of live stalks after lodging implies that lodging reduced the growth rate of stalks.

6.6 Concluding remarks

The collective results of the several re-analyses undertaken in this study offer plausible evidence that stalk death and stalk loss were the major factors that contributed to the apparent 'yield plateau' in the previous studies. The observations on the number of stalks suggested that spatial variations in the number of stalks were potentially a major factor that contributed towards the supposed 'stalk loss' in these studies. The extent to which spatial variations in stalk number were real, or whether there was a systematic tendency to under-retrieve stalks in large, lodged, tangled crops, remains unclear.

The other key finding of this study was that the trash components were likely under-estimated by as much as 60% to 90% in the Ayr and the Macknade experiments, respectively. The partial recovery of trash biomass would have resulted in more than 10% and 15% reductions in the aboveground biomass at the final harvest at Ayr and at Macknade, respectively, further contributing to the perception of a yield 'plateau' later in crop growth.

Meanwhile, there was no evidence that seasonal factors had any large impact on the growth of live stalks in any of the experiments. The live stalks continued to grow throughout the season, with only slight or no slowdown after lodging of the crops.

From these findings, it is concluded that the marked slowdown, and/or complete halt, in biomass production, on a unit area basis, as observed in the previous studies at Ayr and Macknade, was a combined effect of lodging, of the under-estimation of trash components late in crop growth and of sampling variations in stalk numbers, perhaps as a result of either chance spatial variations or systematic problems with sampling large and lodged crops. At Kunia, the main contributing factors seemed to have been the effects of crop lodging *per se*, and of spatial variations in stalk numbers.

The main implications of these findings are that in field experimentation with a large bulky crop like sugarcane, it is important:

1. To perform initial stalk counts of all future sample areas, to eliminate any impact of changes in stalk numbers due to spatial variations in crop growth.

2. To appropriately flag both ends of sample rows before lodging to overcome the problem of intermingling of the stalks after lodging and minimise sampling difficulties once the crops are large.

3. To take into account all the trash components through the use of improved sampling methodology as described by Mazzucchelli *et al.* (1997).

Chapter 7 Summary of conclusions and implications for future research

7.1 Introduction

In the introduction of this thesis, several questions were raised regarding the occurrence of a 'yield plateau' in large and lodged sugarcane crops, and how the growth may be affected by different factors. Under field conditions, sugarcane crops may face a wide range of potential soil and environmental conditions that can affect the productivity. Therefore, the main thrust behind this research was to unravel the causes of the occurrence of a marked slowdown in cane and sugar yield accumulation in large and lodged cane crops prior to the normal time of commercial harvest. This final section brings together the main findings of the study for the purpose of addressing the key project objectives outlined in the thesis introduction (Chapter 1), namely:

1. To determine what factor(s) cause large and lodged crops to slow down biomass production and sucrose accumulation, in some cases, well before the harvest, even when environmental conditions appear to be suitable for high growth rates.

2. To interpret and explain the effect of the identified factors on net growth and death processes as well as on stalk and sucker dynamics, cane yield and CCS.

3. To suggest whether the identified constraints to yield would be best addressed via breeding and/or management options. In, particular, if lodging were found to be an important constraint, alternative methods of selecting varieties for high-yielding environments may be appropriate.

7.2 Lodging and crop growth

The indirect losses due to increased extraneous matter and harvesting costs, resulting from lodging, may be significant and a greater focus on lodging in sugarcane breeding programs can be justified (Jackson *et al.*, 1999). However, it was considered important to quantify the direct effects of lodging and other factors to clarify the causes of the apparent growth slowdown in an appropriate way.

The data obtained in the field experimentation clearly indicated that lodging was a major constraint to high yields in both the dry and the wet tropical environments. Lodging had a significantly large and negative impact on crop growth, sucrose accumulation and hence cane and sugar yield. The effects of lodging were broadly consistent across the seasons and experiments, irrespective of the genotypes, crop sizes and the environments. Prevention of lodging using scaffolding increased cane yield by 11 - 15% (Fig. 3.3 and 4.2a) and sugar yield by 15 - 35% (Fig. 3.4 and 4.2b), depending upon the timing, extent and frequency of the lodging events. There was no evidence that crop age or any of the seasonal factors were implicated in any slowdown of growth in any of the trials. However, none of the treatments experienced a plateau in biomass or sucrose production when all the stalks, viz. live, dead and rat-damaged, were taken into account (Fig. 3.6 and 4.4a).

The effects of lodging on CCS were greatest immediately after lodging, while effects on cane and sugar yield were present and sustained throughout the growth periods after lodging (Fig. 3.5 and 4.3, Table 3.7 and 4.6). Lodging affected a number of crop growth parameters including live stalk number, LAI, light interception, RUE and the rate of biomass and sugar accumulation. A small level of stalk death, i.e., 0.6 - 0.9 stalks m^{-2}, was observed in the lodged control plots (Table 3.7 and 4.7). The yield reductions under lodging were mainly the result of lower weight and sugar content of the live stalks and the reduction in live stalk numbers due to stalk death. There were additional dilution effects from lower CCS of the dead and rat-damaged cane, depending on the nature and extent of lodging and the occurrence of rat-damage. The CCS content of dead stalks was apparently low, i.e., 7.0 - 10.0 units, compared to 15.0 – 18.0 units for the sound live stalks. However, lodging did not result in a 'plateau' in yield accumulation and there was no net loss of 'whole' stalks as reported in the earlier studies (e.g. Muchow *et al.*, 1995).

There was no evidence that crop age had any impact on crop growth rate up to the time of the final harvests. No differences were observed in the growth rates of the live stalks between young and older non-lodged crops (Fig. 3.17 and 4.10, Table 4.8). This does not support the hypothesis that crop age is a limiting factor to high yields in 12 - 15 month crop cycles, at least in the tropical environments where these trials were conducted. This conclusion is well supported by Hawaiian studies, where crops continued to accumulate cane and sucrose yields beyond 18 months of age (Evensen *et al.*, 1997).

Similarly, there was no evidence that seasonal factors were implicated in any slowdown of growth in any of the trials. At all sites, both the scaffolding and late crop treatments continued to accumulate biomass until the final harvests (Fig 3.6 and 4.4a). The one minor exception was at Ayr, and in that instance, the available evidence suggested the cause of the growth slowdown was water stress after irrigation was withheld to allow the ground to dry prior to harvest.

In the current studies, the observed mean temperatures (Fig. 3.1 and 4.1a) during the winter months remained well above the minimum threshold value of 8 - 10°C reported for sugarcane growth under South African (Inman-Bamber, 1994) and Australian (Robertson *et al.*, 1998) conditions. Thus direct effects of cooler temperature (e.g. mean temperature <15°C) on crop growth could not be ruled out in other environments and seasons. Likewise, the effects of other seasonal changes (e.g. radiation levels, humidity, and daylengths etc.) outside the range of those sampled here cannot be absolutely discounted.

While the present studies confirmed the hypothesis from earlier research that lodging seriously constrained crop productivity, there were some important inconsistencies between the current research and the previous studies. Most importantly, in contrast to the earlier research, there was no evidence of a 'yield plateau' or of any physical stalk loss due to deterioration in the current studies.

In order to strengthen the conclusions from the present research concerning the causes of the observed slowdown in growth, it was considered important to identify the causal factor(s) responsible for the apparent 'yield plateau' in the previous studies. If the 'yield plateau' could be explained in terms consistent with the conclusions from the present studies, it would strengthen these conclusions.

The re-analysis of three key previous data sets, two from Australia and one from Hawaii supported the original conclusions about the importance of lodging. However, the re-analyses suggested that, to the extent that it implied that growth had ceased, the observed 'yield plateau' may not have been real, but may have been an artefact of the experimental procedures used in the earlier studies. Firstly, there was strong evidence that, in the Ayr (1991/92) and the Macknade (1992/93) studies, systematic under-estimation of the trash components biased downwards the estimates of crop biomass, and hence accentuated the observed growth slowdown that occurred after lodging. It is plausible that this bias was magnified where the lodged crops smothered trash and dead leaf, and promoted its decomposition.

Secondly, the re-analyses raised serious doubts about the sampling accuracy for large lodged crops, in situations where stalk counts had not been made prior to lodging. In the earlier Ayr and the Macknade studies, and the Kunia (1991/93) study, the observed slowdowns in growth late in the season were associated with, and could be partly (and in the case of Kunia, largely) explained by spatial variations in stalk numbers late in the season. The causes of the stalk variations remain unexplained. However, the explanation of Muchow *et al.* (1995) that the smothered stalks had 'disappeared' in the relatively short time since lodging was unconvincing. More likely, the changes were due to spatial variations in stalk density and/or to difficulties of retrieving all the stalks during sampling in large, lodged crops where stalks are tangled and intertwined.

Whatever their cause, the variations in stalk number were sufficiently able to explain the apparent 'yield plateau' to obviate the need to look for other reasons. Indeed, in the case of Kunia, the spatial stalk variation was a major factor that resulted in the late season 'yield plateau' in this study.

To summarise, the observed 'yield plateau' in the re-analysed studies was able to be explained by the very real effects of lodging, combined with sampling biases associated with incomplete recovery of trash late in crop growth, and unexplained declines in stalk numbers for samples taken after lodging. The re-analyses strengthened the conclusions drawn from the current studies that lodging can provide a serious constraint to growth and yield in large crops in the Australian tropics, and that other factors like crop age and seasonal effects need not be invoked to explain observed responses.

7.3 Industry importance and implications for future research

The research implications of the conclusions from this thesis are appropriately considered in terms of the immediate actions that might be taken, and then the longer-term actions needed in the context of the industry significance of the work.

In the short term, there is potential to improve the accuracy and reliability of sugarcane crop growth simulation models. Lodging is a widespread industry phenomenon, and as discussed at length earlier in this thesis, current simulation models do not adequately describe crop growth once lodging occurs. Models can be improved through the incorporation of routines that capture the various effects of lodging on stalk growth and development identified in the current studies. Model improvements need to be validated against existing data sets where lodging was experienced, several of which are available in 'SUGARBAG'.

To initiate the process of model improvement, a framework for interpreting lodging effects on yield, as described in chapter 4, has been submitted to APSIM-Help for consideration to incorporate in the APSIM sugar module. The participation and assistance of Dr Shaun Lisson, from the CRC for Sustainable Sugar Production and CSIRO Sustainable Eco-Systems, in that task, is acknowledged.

Again in the short term, the re-analysis of the previous data sets indicated that in sugarcane field experimentation, it is important to avoid opportunities for systematic bias and/or sampling errors. The apparent difficulties with sampling of large lodged crops can perhaps be reduced, or if they occur, at least be accounted for, if initial stalk counts are taken before lodging in pre-marked sample areas. This would eliminate any impact of change in the number of stalks due to chance spatial variations on crop growth, and allow any sampling difficulties in retrieving stalks from large, lodged and tangled crops to be recognised and accounted for. It is also important to take into account all the trash components through the use of improved sampling methodology as described by Mazzucchelli *et al.* (1997). This strategy avoids losses due to trash deterioration offsetting ongoing increases in live stalk weight.

Finally, and most importantly, there are longer-term implications from the current work for sugarcane crop improvement research if potential opportunities for productivity improvement are to be realised. The current studies indicated a potential income gain for cane growers by prevention of lodging. However, considering the high amounts of EM in the harvested cane from a lodged crop, the economic losses from the whole of industry perspective can be far more, due to additional harvesting, transportation and milling costs. Clearly, there is potential to improve both the industry productivity and the profitability by addressing this issue in an appropriate way. Improved harvesting, cleaning or processing methods do not directly address the constraints posed by lodging. There is considerable scope to address this issue either through a program for selecting improved varieties less susceptible to the effects of lodging, better crop management to minimise the effects of lodging, or a combination of both. In Australia, no or little attention is currently given to either.

7.3.1 Agronomic management

There are reports from some countries where sugarcane is grown manually that lodging can be controlled to some extent through better agronomic management (e.g. Gangwar and Sharma, 1995). However, due to various economic reasons it is difficult to apply these agronomic management practices under Australian conditions.

These labour-intensive agronomic management practices include deep planting, high hilling-up, stool shaving (ratoon crops) and stalk 'tying'. While the first two options may be practical in plant crops (BSES, 1985), they are likely to be difficult to implement in areas under irrigation or green trash blanketing where a major objective is to minimise soil disturbance. Improved nutrient management may reduce lodging, and use of growth regulators and changes in planting arrangement (e.g. high density planting) may also have a positive effect in reducing lodging. However, there is currently little or no documentation recommending how either should be used to reduce the impact of lodging while balancing other possible effects.

7.3.2 Improved variety selection program

The other option to address this issue is selection for lodging resistant varieties that do not lodge during a normal growth year. Substantial success has been achieved in other field crops through the selection of lodging resistant varieties such as wheat, rice, oats, maize and soybeans (Pinthus, 1973; Fischer and Wall, 1976; Cooper, 1985; Flintham *et al.*, 1997; Menz and Hallauer, 1997).

It is known that sugarcane varieties differ greatly in propensity to lodge (Skinner, 1960; Breaux, 1971). Given this and the economic importance of lodging, it is possible that lodging resistance could be used in a selection index at various selection stages in breeding programs in association with other economically important traits.

The first step, in selection of lodging resistant varieties, requires the characterisation of various parameters that could be used to measure genetic variation and heritability in lodging propensity. Various traits that could be useful predictors of lodging propensity include stalk diameter and stalk height (Breaux, 1971; Sharma and Khan, 1984), internal anatomy (Khanna and Panje, 1939; Negi and Khanna, 1961), root depth and density (Venkataraman, 1957) and the force needed to pull stalks to a certain angle (Skinner, 1960; Amaya *et al.*, 1996).

As the severity of lodging usually varies greatly in different parts of a field, when small selection plots are used, a variety may either be protected, or alternatively pushed over, by varieties in nearby plots, giving a false erectness performance. For example, in the early stages of breeding selection, when small plots are used, erect canes would be disadvantaged if nearby lodging canes were to fall and smother the growth of the erect canes. Thus, the behaviour of a variety in a small plot trial in relation to lodging may relate poorly to behaviour in a pure stand. Given this, an examination of the effect of plot size on selection for or against lodging resistance and the identification of target environments could be also warranted to improve the selection systems compared with the current procedures.

7.4 Concluding remarks

The work reported in the thesis conclusively demonstrated that lodging is a major constraint to the productivity of sugarcane crops in tropical Australian environments. This was hitherto largely unrecognised in the Australian context. The conclusions were strengthened by re-analyses of earlier data that offered plausible explanations of apparent inconsistencies. The research described the physiological basis of the lodging responses, providing a basis on which future crop improvement research might build to overcome the problems. Overcoming lodging through breeding will be a long-term effort but the effects of lodging are sufficiently large to justify the research investment to overcome this problem.

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Appendices

Appendix I *List of abbreviations and symbols*

ANOVA - analysis of variance
APSIM - agricultural production systems simulator
BD - bulk density ($g\ cm^{-3}$)
CCS - commercial cane sugar (%)
DAP - days after planting
DAR - days after ratooning
DM - dry matter ($g\ m^{-2}$)
DUL - drainable upper limit (volumetric water %)
EM - extraneous matter
fi - fractional light interception
k - extinction coefficient
LAI - leaf area index
LL - lower limit (volumetric water %)
NAR - net assimilation rate ($g\ m^{-2}$)
OC - organic carbon (%C)
PAR - photosynthetically active radiation (0.38 - 0.74 µm; $MJ\ m^{-2}$)
PAWC - plant available water content (mm)
RUE - radiation use efficiency ($g\ MJ^{-1}$)
S - cumulative daily incident radiation ($MJ\ m^{-2}$)
SE - standard error
SER - stalk elongation rate ($cm\ day^{-1}$)
Si - cumulative seasonal radiation interception ($MJ\ m^{-2}$)
SLA - specific leaf area ($m^2\ g^{-1}$)
SGR - stalk growth rate ($g\ day^{-1}$)
SR - solar radiarion ($MJ\ m^{-2}$)
SWDEF - soil water deficit factor
TT - thermal time (°C days)
TVD - top visible dewlap
Wt - weight (g or kg)

Appendix II Framework for improving the simulation methodology of lodging in APSIM-Sugarcane (change request submitted to APSIM-Help).

Background

Lodging (falling of crops due to stem or root failure) is a common phenomenon in cane growing. Field experiments were conducted, in the wet and dry tropics, to quantify the impact of lodging on yield accumulation. The growth patterns of lodged and non-lodged cane grown under otherwise identical conditions were analysed in these studies.

Lodging influenced various crop growth processes including stalk number, LAI, radiation interception and RUE, and biomass and sucrose accumulation, resulting in a reduction of cane and sugar yield. It is important to incorporate this quantitative information into crop growth simulation models to assess the impact of lodging on productivity under different conditions.

In APSIM-Sugarcane, lodging effects are accommodated only via a specified rate of stalk death, which is linearly related to water stress (stress_lodge). This represents an approximation to the overall decline in biomass accumulation associated with a range of lodging effects. At a stress_lodge value of 1.0 (i.e. no stress), the rate of stalk decline is set to 0.0025 times the current stalk number. This rate of decline increases up to 0.005 for a stress_lodge value of 0.

Initial attempts to simulate the above-mentioned trials using the existing simulation methodology gave mixed results with close agreement for some variables, at some sites. Briefly (there is a longer report available on request), biomass and sucrose tended to be over-estimated in the lodged simulations.

Furthermore, the model did not capture the (limited) recovery of the crops after lodging. With this in mind, we are proposing a series of changes to the current approach used in APSIM based on the findings from the field trials. These changes will be calibrated against the above-mentioned field trials and then independently validated against data for other lodged trial crops in 'SUGARBAG'.

Supporting results

Lodging had a consistently large and negative impact on crop growth and yield accumulation processes such as:

Stalk number

Lodging increased the number dead stalks apparently due to stalk breakage/smothering effects. A reduction (0.1 stalk m^{-2}) in the number of live stalks was observed at the samplings conducted after lodging.

Leaf area per stalk and leaf area index (LAI)

Compared with non-lodging treatment, lodging increased ratio of dead leaves to green leaves per stalk, reducing the green leaf area per stalk. This led to a reduction (10 - 25%) in LAI of the crops in the lodging treatment.

Radiation interception and radiation use efficiency (RUE)

Lodging had a consistently large impact on radiation interception, leading up to 10 - 15% reductions (instantaneous measurements with a Ceptometer and external sensor) compared to the non-lodging treatment. This was a combined effect of lower LAI and breakdown of canopy architecture due to lodging. However, crops re-established their canopies few weeks after the lodging event, but the daily radiation interception remained < 80%. In addition to this, lodging also reduced RUE of the crops by about 10 - 15%.

Sugar accumulation

Compared with the scaffolding treatment, lodging also slowed (5 - 15%) the rate of sugar accumulation. However, it later recovered depending on the extent and frequency of lodging events.

Live stalk weight

Non-lodging treatment also produced significantly greater cane dry weight per stalk than the lodging treatment at the harvest conducted immediately after lodging. However, crops recovered from this effect towards the end of season.

The effects of lodging on CCS and cane dry weight disappeared with time, while effects on LAI, radiation interception and RUE were present and sustained throughout the growth periods after lodging.

Proposed framework/changes

The following framework is suggested to modify various crop growth parameters (with user defined options) in relation to lodging:

Stalk death

The current modelled rate (0.017 stalk m^{-2} day^{-1}) of stalk death due to lodging is very high as compare to observed rate (0.006 stalk m^{-2} day^{-1}) of stalk death. Hence, there is a need to reduce this rate of stalk death.

Leaf appearance rate

The effect of lodging on LAI and ultimately on the radiation interception can be captured via a reduction, with a slight recovery over time, in leaf appearance rate after lodging.

Radiation use efficiency (RUE)

An adjustment is required to RUE of the crops during the post lodging periods. Currently, model works on RUE of 1.80 g MJ^{-1}, this need to be reduced to a constant rate of about 1.60 g MJ^{-1} after lodging.

Partitioning of dry matter to sucrose

The impact of lodging on sucrose accumulation can be captured with a temporary shift of less biomass partitioning towards sucrose pool and then a recovery to the original values over time.

Appendix III Publications relevant to the thesis

III.1 Paper presented at the 21st annual conference of the Australian Society of Sugar Cane Technologists, Twonsville (1999).

III.2 Paper presented at the 22nd annual conference of the Australian Society of Sugar Cane Technologists, Bundaberg (2000).

III.3 Paper published in the Australian Journal of Agricultural Research, CSIRO Publishing, Vol 53, 2002 (11).

Singh, G., Chapman, S.C, Jackson, P.A., and Lawn, B.J. (1999)
Yield accumulation in sugarcane under wet tropical conditions:
effect of lodging and crop age. Proceedings of the Australian
Society of Sugar Cane Technologists, 21 . pp. 241-245.

Singh, G., Chapman, S.C., Jackson, P.A., and Lawn, R.J. (2000) Lodging: a major constraint to high yield and CCS in the wet and dry tropics. Proceedings of the Australian Society of Sugar Cane Technologists, 22 . pp. 315-321.

Singh, G., et al (2000) Lodging reduces sucrose accumulation of sugarcane in the wet and dry tropics, Australian Journal of Agricultural Research, 53. pp. 1183-1195.