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MODELLING VARIETY DIFFERENCES IN CANOPY GROWTH AND DEVELOPMENT OF SUGARCANE (*Saccharum officinarum* L.) USING CANEGRO

by

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DECLARATION

I declare that the results contained in this thesis are from my own original work except where acknowledged

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TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF APPENDICES

Page

Appendix 1: Weather data

Appendix 2: Leaf emergence data

Appendix 3: Leaf population data

Appendix 4: Leaf angles and ELADP

Appendix 5: Tiller and stalk population, tiller and stalk height, internode numbers per stalk and canopy heights

Appendix 6: Leaf area data

Appendix 7: Model evaluation data for CANEGRO version 1 and version 2.

ABSTRACT

Crop models have great potential as research tools, for crop system management and policy analysis. One of the most promising future uses of crop models is in crop improvement. The limitation in the use of models for crop improvement has been the inability of crop models to predict variety differences. Currently, the CANEGRO model, a sugarcane crop model developed the South African Sugar Association Experiment Station (Inman-Bamber, 1991a) can only model the performance of the NCo376 variety.

Experiments were undertaken in the South East Lowveld of Zimbabwe, which is a hot and dry environment where sugarcane is grown under irrigation, to examine the canopy growth and development of four commercial varieties, ZN6, ZN7, N14 and NCo376. The study aimed at determining variety differences in canopy (tillers and leaves) development, develop parameters that can be used to model variety differences and test the improved CANEGRO canopy model for its ability to predict variety differences in canopy growth and development.

For the late season, the numbers of leaves and tillers produced by each variety were counted every fortnight throughout the crop cycle. The total leaf area of the varieties and the individual leaf area on a stalk were determined using a Delta-T leaf area meter every fortnight. The date of emergence of successive leaves on a stalk was recorded daily. The leaf angles of each variety were measured every fortnight. The amount of photosynthetically active radiation (PAR) intercepted by the varieties was measured using a SunScan Ceptometer. Tillering and tiller senescence rates, phyllochron intervals, extinction coefficients and base temperatures were determined for the growth and development processes of varieties ZN6, ZN7, N14 and NCo376.

Tiller and leaf population development was varietal. Tillering and leaf emergence were highly correlated to thermal time while tiller and leaf senescence were less correlated to thermal time. The poor correlation of the senescence phases to thermal time could mean that tiller and leaf senescence was driven by other factors other than thermal time. PAR interception could be one of these factors. The data showed that PAR interception could be a trigger of tiller senescence.

The study showed that the tiller and leaf population development could be approximated by two linear equations. Tillering will be the first linear phase and tiller senescence the second linear phase. The first linear phase is driven by thermal time. While the second linear phase is triggered by PAR interception, the major driving factors need to be determined. This study proposed the use of two linear equations to model tiller and leaf population development as opposed to the polynomial equations used in the current CANEGRO model. Polynomial equations assume the factors driving tillering and tiller senescence are the same.

The green leaf numbers per plant showed that all varieties experienced a decline in green leaf numbers with crop age. Varieties NCo376 and ZN7 had the greatest decline in green leaf numbers per plant while varieties N14 and ZN6 had the least decline. Variety ZN7 had the highest number of green leaves per plant while NCo376 had the least.

The tiller growth and development was divided into three phases: the exponential phase during the initiation of stalks, the first linear phase during a period of rapid stalk elongation and the second linear phase during sucrose accumulation and maturation. The first two phases of development were driven by thermal time while the sucrose accumulation was not. There were variety differences in tiller growth and development.

There were variety differences in base temperature for the development of various components of the canopy. Internode formation occurred at lower air temperatures than stalk elongation and tillering while canopy heights were correlated with higher air temperatures. This implies that internode formation could occur under conditions unsuitable for stalk elongation and may explain the short internodes frequently observed in stalks exposed to winter during rapid stalk elongation.

The basic requirements for physiological parameters are that they should be stable across different environments, have significant differences between varieties and have physiological meaning. The parameters studied were thermal time requirement for shoot emergence, leaf appearance, to reach peak tiller population and to start of stalk elongation; surface area of the youngest biggest leaf, leaf number of the youngest biggest leaf, PAR transmission at the start of tiller senescence, extinction coefficients, and peak and mature tiller population. The difference between varieties in thermal time to shoot emergence was least using a base temperature of 16 °C compared to using 10 °C and therefore 16 °C could be a more appropriate base temperature for shoot emergence. The accumulated soil temperatures were less variable than accumulated air temperature and could therefore be a more reliable driver of shoot emergence. However, the limitations in the use of soil temperature are that it is not a readily available measurement and that it is not easy to measure.

The gradual increase in phyllochron intervals appeared to be a better method of predicting leaf appearance compared to using a broken stick model. The phyllochron gradient was proposed, as it is likely to be a more robust way of modelling leaf appearance. The varieties had different phyllochron gradients. Variety ZN7 had highest rate of leaf appearance and produced the highest number of leaves per stalk while NCo376 had the lowest rate and produced the least number of leaves.

There were statistically significant differences between varieties ($P = 0,05$) in PAR transmission at the start of tiller senescence and a base temperature of 16 °C was best at determining accumulated thermal time to the start of tiller senescence. Varieties with higher peak tiller population had higher final tiller population, lower thermal time per tiller and a higher ratio of final to peak tiller population.

There were differences between varieties in the youngest leaf number attaining maximum leaf area and the leaf area of the youngest biggest leaf. Variety N14 had the biggest leaves and NCo376 had the smallest. Variety N14 had the highest leaf area index (LAI) while ZN7 had the lowest.

There were significant differences ($P = 0,01$) in PAR intercepted by the varieties but there were no significant differences in extinction coefficients. Extinction coefficients increased with crop age. The varieties had significantly different ($P = 0,01$) leaf angles and ellipsoidal leaf angle distribution parameters. The measurement of LAI using SunScan ceptometer provided a better estimate of extinction coefficients than LAI measured using Delta-T leaf area meter.

Model evaluation showed that CANEGRO canopy model version 2 was improved compared to than version 1. The model (version 2) was accurate in predicting tiller heights and dead leaf numbers per stalk. It was fairly accurate in predicting green leaf numbers per plant, stalk population and intercepted PAR but was poor in predicting LAI. Version 2 has proved to be a substantial improvement over version 1 in predicting stalk population. Generally, the version 2 model overestimated tiller heights early and underestimated later, overestimated the tiller population and LAI after peak, underestimated green leaf numbers per stalk for varieties ZN6, ZN7 and N14 and overestimated dead leaf numbers per stalk and intercepted PAR. The version 2 model predicted a constant green leaf numbers per plant and LAI from peak to harvest while observed data showed that green leaf numbers per stalk and LAI decreased towards harvest. Version 2 model predicted the tiller population of NCo376 closely but underestimated tiller senescence in N14 and also underestimated final tiller population in varieties ZN6 and ZN7. Future model refinements may need to focus on the prediction of the sigmoid pattern of tiller heights. The model may need to be calibrated to predict the green leaf numbers per stalk accurately, which should possibly improve the prediction of LAI that in turn could improve the prediction of intercepted PAR. The improvement in the timing and rate of tiller senescence should improve the prediction of tiller population particularly in varieties ZN6, ZN7 and N14.

The study showed that the broken stick method is superior in explaining leaf and tiller population development compared to using polynomial equations. The development of variety parameters helped improve the prediction of variety differences in canopy growth and development.

A major weakness of most crop models is modelling variety differences in canopy growth and development. The inability of crop models to predict variety differences has limited their use in

plant breeding. This study has resulted in an improved version of CANEGRO version 1 that is an initial attempt at modelling variety differences of sugarcane.

Chapter 1 INTRODUCTION

The ability of simulation models to predict growth and development as affected by soil and weather conditions, agronomic practices and cultivar traits may make such models attractive tools for crop improvement (White, 1998). Models have been used to examine the effects on yield of specific traits or suite of traits representing possible crop ideotypes. Models are highly suitable for aiding breeders in understanding genotype by environment interaction. Mechanistic and comprehensive models can be used to mimic genetic characteristics of plants. Crop models have been used to hypothesize genetic traits for optimizing yields of soy beans, groundnuts and cotton (Boote *et al.*, 1996).

The above was possible because models provided a means of integrating physiological knowledge, variety traits and environmental data to generate new information. However, at present most models lack the ability to simulate differential responses of varieties to the environment. CANEGRO, a sugarcane model, can only model the performance of variety NCo376 (O'Leary and Kiker, 2000).

The ability to model variety differences will aid growers in choosing appropriate varieties for specific growing conditions. Choosing appropriate varieties for specific growing conditions can enhance sucrose production (Zhou, 2001, 2002, Zhou *et al.*, 2002).

Since biomass production is dependant on the amount of photosynthetically active radiation (PAR) intercepted by the canopy, the ability of models to accurately predict yields of different varieties may largely depend on accurate descriptions of canopy development. The ability to model canopy development of different varieties will help in selection of crop starting time to maximize the yield potential of a range of varieties (Singels and Donaldson, 2000). For example, Inman-Bamber, (1994b) suggested that N12 be ratooned in winter because it develops a canopy relatively slowly compared with NCo376. The ability to model canopy development would help in providing accurate prediction of when canopies shade out weeds and thus aid weeds management programmes (Inman-Bamber, 1994b).

In South Africa, the outbreak of eldana borer resulted in the reduction of crop age of harvested cane as a way of reducing pest damage. This resulted in lower yields as younger and immature crops were harvested (Inman-Bamber, 1991a). Developing cultivars with rapid canopy development could reduce the negative effects of harvesting younger crops (Inman-Bamber, 1994a). The ability to model variety differences in canopy development would help in the breeding and selection for such varieties by identifying canopy parameters and characteristics that promote rapid canopy development.

The main components of the sugar cane canopy are stalks (tillers) and leaves. Stalks are grouped together as stools. Stalk heights, canopy heights and leaf emergence differ among varieties. Leaves emerge according to defined phyllochron intervals and the leaf area development differs among varieties. Growth of stalks and leaves is influenced by growing and weather conditions. Leaf sizes and stalk characteristics are genetically and environmentally controlled. The canopy structure and development influence radiation interception, extinction coefficients and radiation use efficiency via leaf area index (LAI). Although the above are logical facts, it is not clear how canopy development and structure differs between varieties. The aim of this study is to identify the differences in canopy growth and development among four varieties (ZN6, ZN7, N14, NCo376) by studying their tiller/stalk and leaf area growth and development. The study also aims to determine photosynthetically active radiation (PAR) interception, extinction coefficients and phyllochrons and base temperatures for these varieties. This study should improve the description of variety parameters in CANEGRO canopy development model and help identify variety parameters for inclusion in CANEGRO.

Factors that affect tiller population also affect PAR interception and consequently cane production (Singels and Smit, 2002). Since biomass production is dependant on the amount of radiation intercepted by the canopy, the ability of models to accurately predict yields of different varieties may largely depend on accurate descriptions of canopy development (Singels and Donaldson, 2000).

There are several sugarcane models in use throughout the sugarcane growing regions of the world. The two main sugarcane simulation models currently in use throughout the world are the Australian model APSIM-Sugarcane (Keating *et al.*, 1999) and the South African model CANEGRO (Inman-Bamber, 2000). The CANEGRO model has been included into the Decision Support System for Agrotechnology Transfer (DSSAT Version 3.1) suite of models as CANEGRO Version 3.10 that has been used throughout the Americas, Africa and Asia (O'Leary, 2000). CANEGRO was chosen for this study because it has been developed and tested on variety NCo376 in South Africa (Inman-Bamber, 1991a, 1994b; O'Leary 2000) and variety NCo376 is a major variety in Zimbabwe while N14 is the second most widely planted variety in Zimbabwe (Zhou, 1998a). Therefore CANEGRO is likely to be a more suitable model for Zimbabwe after calibration and validation for hot, dry and irrigated cane growing conditions.

The origins of CANEGRO date back to the 1970s. It was first assembled as CANESIM in 1991 (Inman-Bamber, 1991a). The model comprises a carbon simulation, crop development and energy and water simulation components (O'Leary, 2000). The CANEGRO model now exists in two variations, the stand-alone South African Sugar Association Experiment Station (SASEX) variation used exclusively by SASEX as a research tool and the DSSAT version 3.10 sugarcane model (O'Leary, 2000).

Simulation models vary in the level of detail that describes genetic differences among varieties. Since the raw material of crop improvement is genetic variation, failure to represent genetic variation limits the utility of models (White, 1998). One of the weaknesses of CANEGRO is modelling varieties other than NCo376 (O'Leary and Kiker 2000). In CANEGRO, the number of parameters that describe different varieties is very low and the biggest need is to determine CANEGRO variety parameters.

The important developmental stages of the stalk component of the canopy are tillering, tiller senescence and stalk elongation. The important developmental stages of the leaf component of the canopy are leaf emergence and leaf senescence. Sugarcane developmental phases are germination and emergence, tillering and stalk elongation to maturity. The tillering phase consists of the germination and emergence of primary tillers, the underground branching and emergence of secondary and higher order tillers and tiller senescence phases (van Dillewijn, 1952 and Cock, 2001). Under suitable growing conditions a typical commercial crop's tiller population will increase rapidly, followed by a phase of tiller senescence before the population becomes stable.

Findings from this study will be incorporated into the CANEGRO canopy model. It is hoped that this new improved canopy model will be evaluated for its accuracy in predicting leaf area index, stalk population, stalk heights, green leaf numbers, dead leaf numbers and PAR interception of the four varieties.

In Zimbabwe all cane is produced under irrigation. The South East Lowveld of Zimbabwe, where cane is commercially grown, is hot and dry and rainfall is low and erratic (Clowes, 1998). This study will add information on modelling sugarcane growth and development under irrigated, hot and dry environments.

1.1 Objectives

The studies aim to identify and determine the differences in canopy development among four varieties (ZN6, ZN7, N14, NCo376) and thus develop variety parameters that could be incorporated into the CANEGRO model. The study also aims to identify those variety differences in canopy growth and development that could be used to improve management of a cane crop to increase yields. These varieties represent high to low stalk population in

Zimbabwe (NCo376 produces 146000; N14 118000; ZN6 100000 and ZN7 84000) (Zhou, 1998b). This variation in stalk population among these four varieties represent the variation found in commercial varieties in Zimbabwe and possibly elsewhere. Variety NCo376 produces smaller leaves while the other varieties produce larger leaves. Variety N14 canopied earlier than other varieties. The influence of variety differences in canopy development on PAR interception and extinction coefficients will be studied together with the determination of phyllochrons and base temperatures of the four varieties. Physiological parameters for modelling variety differences in canopy growth and development will be studied and determined. The determined physiological parameters will be used to develop and improve on the current CANEGRO canopy model. The data measured on the canopy characters (tiller population, tiller heights, leaf area index, green leaf numbers per stalk, dead leaf numbers per stalk and intercepted PAR) will be used to evaluate the current and improved CANEGRO canopy models for their ability to predict canopy growth and development and to identify possible future improvements to the CANEGRO canopy models.

The specific objectives of the study are:

(1) To identify and determine variety differences in canopy growth and development among four sugarcane varieties (ZN6, ZN7, N14 and NCo376) grown under irrigated growing conditions in the South East Lowveld of Zimbabwe.

(2) To determine physiological parameters that could be used for modelling sugarcane variety differences in canopy growth and development using CANEGRO.

(3) To evaluate the current and improved CANEGRO canopy models for their ability to simulate variety differences in canopy growth and development of tiller population, tiller heights, leaf area index, green leaf numbers per tiller, dead leaf numbers per tiller and intercepted PAR.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

A model is a description of a system. A system is any collection of interrelated objects. An object is some elemental unit upon which observations can be made, but whose internal structure either does not exist or is ignored. A description is a signal that can be decoded or interpreted by humans (Haefner, 1996). The value of a particular model depends on the nature of the problem, the aims of the researcher and the type of model chosen (Thornley, 1975).

2.2 Crop models

A crop model is a simplification of the soil, plant and atmosphere continuum and is a simplified description of a system to assist in predictions (Hughes, 1992). Monteith (1996) defined a crop model as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables. Sinclair and Seligman (1996) defined crop modelling as the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers. Models have been published for most of the world's major food crops as well as for cotton, tobacco, grasses and ornamental crops. These models generally describe the development, growth and yield of a crop on a homogeneous area of soil exposed to certain weather conditions (Jones *et al.*, 1994).

Models and theories have the same concepts and ultimate goals, to find truth. A model is a hypothesis and no model is perfect. Models are useful, not because they reproduce reality, but because they simplify it and thereby enable the most important aspects to be identified, studied, simulated and if all is well, predict in advance. Because of the element of simplification, no model should be used to make predictions outside the context in which it was developed or beyond the range of parameter values that it has been validated (Mugabe, 1995).

The objectives of crop modelers have varied from understanding mechanisms of plant growth processes, to assisting in management and decision-making. Although there are considerable differences in mathematical structures, the processes included and levels of detail and mechanism in each model, there are also some major similarities. Most models are deterministic, operate on daily time steps and require weather and soil data that are widely available and produce outputs that are of general interest to people studying crop management or to those interested in decision making and planning (Jones *et al.*, 1994).

2.2.1 Potential uses of crop models

There are three broad categories for potential uses of crop models, as a research tool, for crop system management and as a policy analysis tool (Boote *et al.*, 1996). Models have largely been used as a research tool.

2.2.1.1 Models as a research tool

Crop models are particularly valuable for synthesizing research understanding and for integrating up from a reductionist research process. Crop growth models may be the only way to integrate over the many processes that plant physiologists may study in isolation. Models can be used to examine scientific hypotheses and to highlight where information and understanding is lacking.

Models can be used to integrate knowledge across disciplines. The expertise of soil scientists, pest discipline scientists and economists is sought to address soil and pest related factors and to evaluate the profitability of crop management strategies. Crop models have been used to organize data from many experiments. Crop models have been used to hypothesize genetic traits for optimizing crop performance using sensitivity analysis of the genetic traits. Crop models have been used for yield gap analysis between the climatic potential and the observed yield (Inman-Bamber, 1995; Muchow *et al.*, 1997).

Models as a mathematical basis for hypotheses enable progress to be made towards a quantitative understanding of plants and their response to the environment. An attempt at model construction can often help in pinpointing areas where knowledge and data are lacking. Models can stimulate new ideas and experimental approaches. Models may give a reduction in the amount of *ad hoc* experimentation, enabling the design of experiments to answer particular questions and discriminate between alternative hypotheses. Compared with traditional methods, models often make better use of data, which is becoming increasingly precise but more expensive to obtain. Information on different aspects of plant growth can often be brought together, giving a unified picture, and sometimes providing a valuable stimulus to collaboration and teamwork. A model frequently provides a convenient data summary. Models can give a method for interpolation, extrapolation and prediction. A successful model may be used to suggest priorities for applied research and development, and if used cautiously, to aid the crop manager in taking decisions (Thornley, 1975).

2.2.1.2 Model use for crop system management

Crop models have been used in cultural management to assist in optimizing planting date (Inman-Bamber, 1994b), planting density, row spacing, and variety choice and fertilizer application for different soil types. Crop models have also been used to assist water and fertilizer nitrogen management and site specific or prescription farming (Boote *et al.*, 1996).

2.2.1.3 Model use for policy analysis

Crop models have been used in best management practices to reduce fertilizer and pesticide leaching and soil erosion. Models have also been used for yield forecasting (Bezuidenhout, 2001; Bezuidenhout and Singels, 2001) and in evaluating climate change effects (Boote *et al.*, 1996).

2.2.2 Minimum data set (MDS)

The minimum data set for a model is that minimum required by the model before it can simulate outcomes. The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project has defined the minimum data set required for crop model validation under local conditions. The IBSNAT crop models use nine data files: daily weather data, soil profile properties, soil nitrogen dynamics, soil profile initial conditions, irrigation management data, nitrogen fertilizer management data, genetic coefficients and crop specific coefficients (Hoogenboom *et al.*, 1994). The minimum weather data set includes air temperature (minimum and maximum), solar radiant density, rainfall, wind speed, water vapour density and relative humidity (Savage, 1998b).

2.2.3 Model evaluation, calibration and validation

2.2.3.1 Model evaluation

Performing simple linear regression and testing for a unit slope with a zero intercept is a method used to evaluate crop models. Using the statistics defined by Willmott (1982), statistics such as the systematic and unsystematic mean square errors may be calculated. Ideally, for a perfect model, the ratio of the systematic to the total mean square error should be 0,0 and the ratio of the unsystematic to the total mean square error should be 1,0 (Savage, 1998a). The use of the correlation coefficient as an index of agreement has limitations. It does not show any cause or effect of a relationship.

2.2.3.2 Model calibration

Calibration is adjusting certain model parameters or relationships to make the model work for your site (Boote *et al.*, 1996). Calibration of a model involves changing certain parameters so that the model agrees with experimental data (Savage, 1998b). Certain model subroutines might need several calibrations before the model can be used (Wegener *et al.*, 1988). When calibrating a model, it is very important that a given parameter be altered for a good reason. Generally as the system one is trying to simulate gets more complex, the model versus experimental data may agree less and less because a large system has more parameters (Savage, 1998b).

2.2.3.3 Model validation and validation methods

Validation is defined as the process in which the model is tested against data that have not been used during the calibration of the model (du Toit, 1995). Boote *et al.*, (1996) defined validation as determining whether the model works with totally independent data sets, that is, if it can accurately predict growth, yield and processes. MacRobert (1993) stated that one of the important requirements to be met before a crop model can be employed for decision-making is to verify that the model is technically correct for the given task. Savage (1998b) defined validation as the process whereby the modeler compares the model outputs with experimental data. He argued that the modeler must validate parts (sub-routines) of the model in addition to the whole model. The modeler must compare timing of events, particularly in the case of crop yield modelling. Germination, emergence, emergence of leaves and tillering are important phenological events that the modeler must ensure that the model is in phase with. Prediction of such events too early or too late can have adverse effects in the final prediction of yield. The model is tested against the reasons for building the model, the use to which the model will be put and purposes of the design (Dent and Blackie, 1979). When validating a model, it is important to use an experimental data set that was not used in establishing the model, otherwise the model will appear to be in very good agreement with measured data but when used with a truly independent data set, may appear poor in predicting actual events (Savage, 1998b).

A common method of model validation involves validating each subroutine using an experiment. It is best to progress from simple to complex systems, validating simple systems first and then the more complex system. Validation of the simpler sub-routines before the whole model assists in tracing where the model no longer describes physical events of the real world (Savage, 1998b). Savage (1998b) suggested three ways in which the validation problem can be approached: (1) use of statistical methods to test whether the actual and model generated timing of events agree; (2) regress generated data against actual data; (3) perform a factor analysis on the set of generated time paths and a second factor analysis on the set of observed time paths and see if the two factor loadings are different or similar to each other.

2.2.4 Sensitivity Analysis

It is important to know the magnitude of change of a model's output for a given change in each of the input parameters, and how sensitive the model is to each of the input parameters. It is important to know the impact of each input parameter on model output and that is why publications concerning models frequently include sensitivity analysis. Sensitivity analysis diagrams show the effect on an appropriate output from the model of changing the value of each parameter in each direction from the central value. One important check is whether the percentage change in the output is greater or less than the percentage change in the parameter. The ratio of the range in the output to that in the parameter provides a simple measure of sensitivity. Ratios greater than or less than unity suggest sensitivity and insensitivity respectively (Mugabe, 1995).

Sensitivity analysis is a procedure carried out on the completed and at least partly validated model that involves exploring the operation and performance of the model. A sensitivity parameter is one that causes a major change in model output (Dent and Blackie, 1979). Savage (1998b) suggested sensitivity tests of inputs by varying one input at a time while keeping all other inputs constant. The estimated and actual model values are then compared for each change in input value.

Parameter sensitivity analysis involves analyzing differences in model response to small differences in parameter values. Sensitive parameters are those to which we should devote the greatest research effort so as to obtain the best advances in technology, given budget and time constraints (Haefner, 1996).

2.3 Canopy growth and development

2.3.1 Definitions of growth and development

Growth and developmental processes determine the state of a plant. In modelling crop systems, separating the two processes is important because they are affected by different environmental variables. Development refers to the timing of critical events in the life cycle of a plant (Ritchie and Nesmith, 1991). Tesfuhuney (2001) described plant development as stages of anatomical development, which a plant passes through during its growth from emergence to maturity. Plant development may be defined as the sequence of ontogenetic events involving both growth and differentiation, leading to changes in function and morphology (Landsberg, 1975). In designing models of crop growth, a model of the physiological process of development is critical (Waggoner, 1975).

Growth refers to the increase in mass, volume, length or area of some part or all of the plant (Ritchie and Nesmith, 1991). It is the irreversible increase in size of the organ, due predominantly to an increase in cellular water content accompanied by the simultaneous extension and synthesis of the cell wall and accumulation of the solutes (Boyer, 1985). While some define plant growth as a process of cell division and elongation, agronomists generally define it as an increase in dry matter (Fussell *et al*, 1980).

2.3.2 Canopy components of a sugarcane crop

The main components of the sugarcane canopy are tillers, stalks and leaves. The cane plant is composed of four principal parts, the leaf, the stalk, the root system and the flower (King *et al.*, 1965).

2.3.2.1 Tillers

As the primary shoot grows, the stem forms very short joints, on the nodes of which the small buds near the bottom swell and develop secondaries that produce their own root system, and these in turn may develop tertiary shoots in a similar manner. This process of underground branching or tillering results in a number of stalks, forming a stool. The extent of tillering and survival of the tillers to maturity is to some extent a varietal character, but it is also influenced by climatic, soil and nutrient conditions (Barnes, 1964).

2.3.2.2 Leaves

The leaf consists of two main parts, the sheath and the blade. The upper portion of the leaf is known as the blade and the lower section, which is curved round the stalk, is called the leaf sheath (King *et al.*, 1965). Leaves grow from the nodes on alternate sides of the stem (van Dillewijn, 1952; Barnes, 1964; King *et al.*, 1965.). The result is that leaves are borne in two ranks and develop into a fan-like formation (King *et al.*, 1965). In young plants leaves are small and few in number, ranging from small scale-like sheaths without blades at the base and increasing in size as the plants develop after which their length shows a decrease (van Dillewijn, 1952; Barnes, 1964). The sheath is attached to the stalk by a basal ring and completely surrounds the stalk. The sheath and blade are joined by the ligule and the dewlaps form the hinge of the blade joint. The blade broadens from the blade joint and tapers to the tip (Barnes, 1964) and it is strengthened and supported by a midrib extending along its full length (King *et al.*, 1965). The leaf blade varies in length and width. Varieties differ in the extent to which the leaf sheaths adhere to the stalk as growth proceeds. In free-trashing canes, as the older leaves die and dry up, the sheath becomes loose on the stalk and breaks away easily at the point of attachment (Barnes, 1964). The leaf sheath is normally light green in colour, but the blade varies from yellowish green to very dark green depending on both the variety and the nutritional status of the plant (King *et al.*, 1965). The leaf edges are generally serrated, and the leaf sheaths are frequently clothed with a growth of fine hairs that in some varieties make handling unpleasant (King *et al.*, 1965).

2.3.2.3 Stalks

The stalk may be defined as the above ground portion of the plant that carries the leaves and the flower. A small portion of the stalk is below the ground, but this is normally referred to as the stubble or root-stock (King *et al.*, 1965; Singels and Smit, 2002). The cane stalk is approximately cylindrical in cross-section and is composed of a number of sections or internodes (King *et al.*, 1965). The stalk is divided into a number of joints, each consisting of a characteristic ring called the node, and an internode. Lateral buds appear at the nodes, one on each, normally on alternate sides of the stalk (Barnes, 1964; King *et al.*, 1965). During development of the stalk the buds are protected from possible damage by the leaf sheath, which is folded tightly round the internode (King *et al.*, 1965). At the base and top the nodes are very close together, so that a large number of buds occur in these portions. The stalk tends to taper towards the apex, and the young nodes, which are hidden by the overlapping leaf sheaths, are very close together (van Dillewijn, 1952; Barnes, 1964; King *et al.*, 1965). The closeness of the nodes in the basal portion is important in relation to the formation of shoots or tillers and the development of ratoons (Barnes, 1964). The bottom and topmost parts of the stalk display a wide range of variation in length, diameter, configuration, cross-sectional form, colour and alignment. Changes in the length and thickness often occur on the same stalk, being brought about by climatic and crop management factors that cause differences in growth rates. Stalk characteristics also vary with varieties (Barnes, 1964, King *et al.*, 1965).

2.4 Plant canopy structure

Plant canopy structure is the spatial arrangement of the above ground organs of plants in a plant community. Canopy structure affects radiative and convective energy exchange of the plant community, so information about canopy structure is necessary for modelling these processes. The presence and structure of a canopy exert a major influence on the air temperature, water vapour concentration and radiation regime in the plant environment (Campbell and Norman, 1989). Ross (1981) recommended that description of plant canopies should include measurements at four levels of organization: individual organs, the whole plant, the pure stand and the plant community. Ross (1981) suggested that plant heights of the top and bottom of the foliage canopy, stem height and diameter and number of leaves should be determined on a sample of 150 to 300 plants. These primary characteristics are then examined to select 15 to 30 plants to be examined in greater detail to determine average characteristics of individual organs. A description of canopy organization at the pure stand or plant community level requires measurement of the plant population density. Canopy closure is when plants begin to overlap so that it is difficult to discern the outline of a particular plant or row of plants (Campbell and Norman, 1989). Many models used for calculating PAR interception by canopies require information on leaf area index both of which are determined by plant canopy structure.

2.4.1 Methods of sampling for measuring plant canopy characteristics

Three methods are common and these are the direct measurement method, the stratified clip method and the dispersed individual plant method. With the direct measurement method, the sampling volume is large enough to include a relatively large number of plants. Ground areas of 0,25 to 2 m^2 are typical. This is the most useful method in canopies such as grasses where plant densities are high, and studies of individual plant characteristics could be difficult (Campbell and Norman, 1989). This method was used in this study.

The stratified clip method has been used widely in studies of canopy structure. It consists of defining a representative volume of foliage, usually using a wire frame, and dividing the volume into layers in which cane is clipped to determine area (Campbell and Norman, 1989).

Ross (1981) described the dispersed plant method. The method consists of selecting 10 to 30 plants that are representative of the canopy and measuring characteristics of those plants. This method is suited to low densities and large individual plants such as maize.

2.5 Temperature effect on growth and development

Since temperature affects many plant processes including nutrient uptake, water absorption, photosynthesis, respiration and translocation of photosynthate, it is not surprising that temperature is considered the most important environmental factor governing plant development (Coelho and Dale, 1980). Temperature strongly influences the rates of all metabolic processes in living organisms, and therefore affects almost all aspects of the growth and development of an organism (Landsberg, 1975; Campbell and Norman, 1998). An increase in temperature accelerates germination and leaf expansion and so shortens the duration from germination to maturity (Tesfuhuney, 2001).

Since most often it is air temperature surrounding plants that is measured since canopy temperature is more difficult and more expensive to measure, plant growth and development is always compared to air temperature. However, meristerm temperature is the temperature that affects plant growth and development (Savage, 2002, personal communication).

2.5.1 Thermal time concepts

Thermal time, known elsewhere as accumulated temperature or heat units, is not the amount of heat that is transferred from the environment to the plant, but a time scale as perceived by the plant as a function of air temperature (Ong and Monteith, 1985). It is generally used to predict or analyse the rate of plant development such as time to flowering or crop maturity (Cross and Zuber, 1972) and has been widely used for analyzing the influence of the climatic factors in relation to leaf growth (Gallagher, 1979).

The effect of temperature on development rate has been described using thermal time concepts, such as the growing degree-days. It assumes that phenological development is constant per degree of temperature between the base temperature and maximum temperature, below and above which the development rate is zero (Stewart *et al.*, 1998). The development is described by base temperature (T_{base}), optimum temperature (T_{opt}) and maximum temperature (T_{max}). Development is maximum at T_{opt}, below T_{base} and above T_{max}, development is zero (Fig. 2.1). The rate of development increases between T_{base} and T_{opt} and decreases between T_{opt} and T_{max} (Campbell and Norman, 1998).

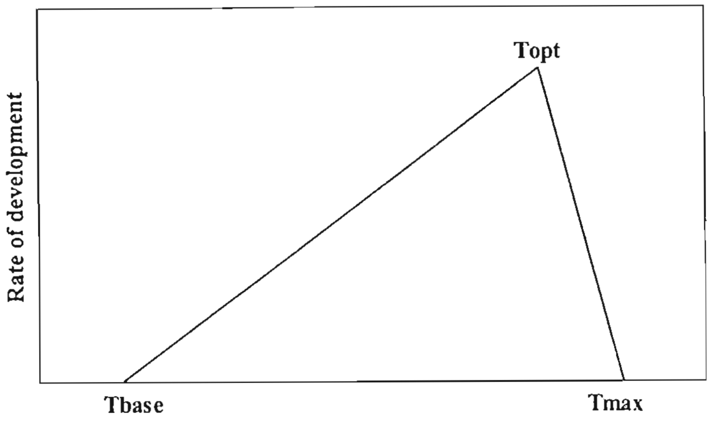


Fig. 2.1 General relationships between temperature and plant development. Base, optimum and maximum temperatures are T_{base}, T_{opt} and T_{max} respectively (adapted from Monteith, 1979)

2.5.2 Calculation of thermal time from weather data

Many methods of calculating heat units or thermal time have been used successfully in agricultural science. In particular, in the area of crop phenology and development, the concept of heat units, measured in growing degree days (GDD °C day), has vastly improved description and prediction of phenological events compared to other approaches such as day of year or number of days after planting or emergence (Cross and Zuber, 1972).

The calculation of thermal time is based on the linear relationship between rate and temperature between T_{base} and T_{opt}, although it can be easily modified to take into account temperature above T_{opt} (Garcia-Huidobro *et al*, 1982, Campbell and Norman, 1998). Thermal time summation is calculated with different formulas but the common one applied is:

$$\tau=\sum_{i=1}^{n}[(T_{\max}+T_{\min})/2-T_{base}] \qquad 2.1$$

where T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature and T_{base} is the temperature below which the plant process of interest does not progress. τ represents the accumulation of thermal time during the growth period. The intent of Eq. 2.1 is to describe the heat energy received by the crop over a given time period (that is integration of the area under the diurnal temperature curve). It is the summation of the daily heat energy over an interval of time and it is then used to relate the accumulation of heat energy to progress in development or growth processes (Tesfuhuney, 2001). A number of scientists have tested the accuracy of various forms of the basic thermal time Eq. 2.1 in predicting various growth and developmental processes in several species.

McMaster and Wilhelm (1997) noted the two types of implementations for calculating accumulated thermal time. The first method was if $[(T_{max}+T_{min})/2]<T_{base}$, then $[(T_{max}+T_{min})/2]=T_{base}$. This method seems to be the most widespread method used for calculating thermal time, particularly in simulation models (Davidson and Campbell, 1983; Kirby, 1995). This method was used in this study. The second method implemented was where if $T_{max}<T_{base}$, then $T_{max}=T_{base}$, and if $T_{min}<T_{base}$, then $T_{min}=T_{base}$. This is the most commonly used method in calculating thermal time for maize, but is used for other crops as well (Baker and Gallagher, 1983; Swanson and Wilhelm, 1996). Occasionally a combination of the two methods is used (Baker and Gallagher, 1983). This kind of systematic calculation of thermal time is important in comparing the effect of temperatures on leaf growth for different planting dates. The temperatures in summer might be higher than optimum, in which case the crop becomes stressed. During summer time in the tropics it is rare for T_{min} to become less than T_{base} (Tesfuhuney, 2001).

2.5.2.1 Temperature extremes and the computation of thermal time

In Eq. 2.1, the daily mean temperature is used to compute the thermal time for a given day. The temperature during the diurnal cycle can vary and be outside the linear portion of the temperature response function (Campbell and Norman, 1998). For example, minimum and maximum temperatures of 15 and 25 and 10 and 30 would give the same mean temperature while representing different extremes, which may affect growth and development differently. The use of the summation of hour-degrees to determine thermal would be more accurate.

Another problem arises when temperatures are high. The computations described only apply for temperature below T_{opt}. Development rate decreases from T_{opt} and reaches zero at T_{max} (Fig. 2.1). The following equations can be used when temperature extremes are experienced (Campbell and Norman, 1998).

$$\begin{aligned}
\tau &= 0 \text{ when } T_{mean} = T_{base} \\
\tau &= (T_{mean} - T_{base}) \text{ when } T_{base} < T_{mean} < T_{opt} \\
\tau &= (T_{max} - T_{mean})(T_{opt} - T_{base})/(T_{max} - T_{opt}) \text{ when } T_{opt} = T_{mean} < T_{max} \qquad 2.2 \\
\tau &= 0 \text{ when } T_{max} = T_{mean}
\end{aligned}$$

2.5.3 Phyllochron concept

The phyllochron is the time interval between the appearances of successive leaves (Hunting and Drennan, 1966). It is the use of thermal time to predict leaf appearance in several crops (Ritchie and NeSmith, 1991) and has been applied to sugarcane in a variety of ways (Inman-

Bamber, 1994b). Ferraris *et al.* (1994) used a base temperature of 15 °C to determine the thermal time requirement for leaf emergence in sugarcane also known as the phyllochron interval or index. Phyllochron 1 is the thermal time for each leaf required for the emergence of leaf 1 to about leaf 14 and phyllochron 2 is the thermal time for each leaf required for the emergence from leaf 14 upwards (Inman-Bamber, 1994b). The leaf number when leaf emergence change from phyllochron 1 to phyllochron 2 is the phyllochron switch.

2.6 Photosynthetically active radiation (PAR)

PAR with wavelengths between 400 and 700 nm is required directly to sustain the growth of all green plants (Treshow, 1970). The top six fully expanded leaves on the stalk of sugarcane intercept most of the PAR in the canopy (Bull and Glasziou, 1975). Growth rate is often proportional to the amount of PAR intercepted by the canopy (Russell *et al.*, 1981) and intercepted PAR determines biomass production (Singels and Donaldson, 2000).

2.6.1 Factors affecting the proportion of PAR absorbed

Absorbed radiation depends not only on the daily photosynthetically active radiation (PAR) received but also on the duration of the various phases of growth. The proportion of incident PAR absorbed depends primarily on canopy structure (Russell *et al.*, 1981).

The structural property of a canopy that has the largest effect on its interception of radiation is the amount of leaf present or green leaf area index (LAI). LAI is the leaf area of green leaves (one side only) divided by the land area under the green leaves. Values of LAI are between 1 and 12 with typical values of 3 to 4 for a good cover of planophile species such as alfalfa, but much higher values of 5 to 10 for more erectophile species such as grasses and cereals (Russell *et al.*, 1981). The distribution of leaf area within the canopy is also important, in addition to the amount of leaf present.

2.7 A case for modelling canopy growth and development of sugarcane

Cock (2001) observed that most sugarcane research was directed at molecular approaches to increase productivity at the expense of crop physiology research. He noted that molecular approaches without deeper understanding of physiological determinants of yield potential are likely to fail. He also noted that the little funding dedicated to physiological research on sugarcane are mainly at cellular and molecular levels with virtually no research, outside Australia, on growth and development at the crop and plant level. Cock (2001) found that rice was the best example where an understanding of the physiology and development contributed to increased yield through development of rice varieties. Research has shown that the understanding of growth and development improved the management of the improved varieties and that increased productivity. Cock (2001) argued that the stagnation in sugarcane yield in Australia and South Africa could be attributed to the lack of understanding of growth and development of the crop.

Biomass production is dependant on the amount of PAR intercepted by the crop canopy (Singels and Donaldson, 2000; Cock, 2001). The ability of models to accurately predict yields of different varieties may largely depend on accurate descriptions of canopy development (Singels and Donaldson, 2000).

Knowing the time it takes for a variety to form a full canopy makes for better selection of starting time to maximize the yield potential of a range of varieties. Inman-Bamber (1994b) suggested that N12 be ratooned in winter because it develops a canopy relatively slowly compared to NCo376 (Singels and Donaldson, 2000).

Accurate predictions of the time when canopies shade out weeds in crops throughout the harvesting season will be valuable for selecting appropriate weeding programs. The time and amount of canopy cover during early stages of crop growth were very different for varieties N12 and NCo376 studied by Inman-Bamber (1994b). These factors should be quantified for other varieties as they also have implications for irrigation practices that could improve water use efficiency.

Leaf area index (LAI) is influenced by leaf appearance rate, leaf size and leaf senescence. Leaf appearance rates depend on stalk number or tillers and leaf appearance rate per tiller (Cock, 2001). A tiller is the smallest individual and self-sustainable unit in a sugarcane crop. Cock (2001) noted that little is known about tillering in cane. Most models, developed to simulate growth and development, do not simulate tillering but assume a fixed tiller population (Inman-Bamber, 1991a, 1994b; Cock 2001).

Each tiller consists of a single stalk with a number of leaves. Tiller density in CANEGRO determines PAR intercepted by the crop canopy. Under suitable growing conditions a typical commercial crop's tiller population will increase rapidly, followed by a phase of tiller senescence before the population becomes stable (Inman-Bamber, 1991, 1994b; Bezuidenhout, 2000; Cock, 2001). Inman-Bamber (1991) and Bezuidenhout (2000) noted that a mature sugarcane crop would have a predictable tiller population. For instance in South Africa, NCo376 produces 133000 tillers, N12 150000, N14 120000 and R570 80000 (Bezuidenhout, 2000). However, in Zimbabwe NCo376 has 146000 tillers and N14 has 118000 perhaps because of different growing conditions such as high temperatures and more sunshine due to low rainfall and less cloud cover.

The CANEGRO model assumes a fixed tiller population and simulation of tiller population was based on empirically fitted polynomial equations (Inman-Bamber, 1991, 1994b). A mechanistic approach to tillering was proposed by Bezuidenhout (2000). He developed a tiller model with five phases, namely, pre-germination, pre-emergence, primary tiller emergence, tillering and tiller senescence phases.

The CANEGRO model (Inman-Bamber, 1991a) simulates canopy cover through a mechanistic approach at a tiller and leaf level. The canopy model does cater for variety differences in a limited way, but does not cater for the effect of row spacing, or ratoon stage on canopy cover. Leaf expansion is calculated from air temperature and adjusted for water stress. Leaf and tiller appearance rates are calculated as functions of thermal time using base temperatures of 10 and 16 °C, respectively (Singels and Donaldson, 2000).

It is known that varieties differ in numbers of millable stalks, sizes of leaves, in rates of emergence and senescence of leaves, phyllochrons and base temperatures (Anon, 1999; Inman-Bamber, 1994b; Bezuidenhout, 2000; Cock, 2001). The canopy differences in varieties may cause differences in PAR interception, extinction coefficients and radiation use efficiencies. These differences should be quantified for incorporation into CANEGRO thereby improving modelling other varieties other than NCo376 (O'Leary and Kiker, 2000).

Van Dillewijn (1952) outlined the effects of PAR, day-length and air temperature on tillering while Inman-Bamber (1994b) noted that heat units (equivalent to the thermal time) could be used to simulate the response of tiller population to air temperature. Ritchie and NeSmith (1991) highlighted the importance of thermal time in modeling crop development.

The above shows that canopy development of sugarcane is largely determined by air temperature. The study by Singels and Donaldson (2000) concluded that air temperature was the most important environmental factor to predict unstressed canopy development. They also concluded that base temperature for canopy development was much higher than previously documented and varieties may have specific base temperatures.

Under normal crop conditions, senescence of tillers is mainly driven by competition for PAR in which younger, less competitive tillers die (Van Dillewijn, 1952). Unpublished results from J. Glover (SASEX, 1973) showed that 75% of tillers that senesce die before they reach a height of 300 mm. Inman-Bamber (1994b) noted that younger tillers die rapidly when 70% of PAR is intercepted by green foliage. Van Dillewijn (1952) highlighted that tillering and tiller senescence was varietal.

This study will aim to improve the understanding of differences in tillering and tiller senescence among the four varieties and how this information can be used to improve modelling the tillering process among varieties.

In the tiller model proposed by Bezuidenhout (2000), the availability of PAR to the individual tiller was assumed to drive tiller senescence. This phase continues until harvest and starts when the youngest tiller in the crop has a leaf area that is lower than a calculated minimum sustainable leaf area per tiller, expressed in terms of leaf area index and stool diameter. All tillers that become unsustainable are immediately removed from the crop. Van Dillewijn (1952) and Inman-Bamber (1994b) agrees with observations of Bezuidenhout (2000) but it is not clear how tiller senescence differs among varieties.

The work by Bezuidenhout (2000) showed an improvement in modelling tillering. When CANEGRO and the tiller model were tested, they underestimated tillering and PAR interception but the tiller model had better estimates. The tiller model defined a fixed ratio between tiller population at harvest and the number of primary tillers that will emerge in the consecutive ratoons and used this ratio to account for differences between ratoons. A stool diameter factor was introduced that contributed to the model's simulation of differences between consecutive ratoons. A minimum sustainable leaf area per tiller under PAR competitive conditions was determined by the stool diameter and LAI and used to simulate tiller senescence in a more mechanistic way. The proposed tiller model could be an improvement to the CANEGRO model's tiller population component. This improvement, however, does not account for variety differences. The above study was done on NCo376 under rain-fed conditions. It is doubtful whether this improvement holds true for all varieties growing under different climatic conditions.

Crop growth, water use and yield are largely determined by the amount of PAR intercepted by the crop canopy (Van Dillewijn, 1952, Inman-Bamber, 1994b). The extinction coefficient is known to vary due to solar angle and leaf angle. While solar angle is very predictable, little is known about the effect of the variance of leaf angle in sugarcane. Some sugarcane cultivars have early prostrate growth habit (e.g. N14) while others have a dominant vertical growth (e.g. NCo376). These markedly different growth habits result in varying leaf orientations to solar radiation. Similarly leaves of individual cane varieties vary from being almost vertical to the stem to almost perpendicular to the stem. Thus the use of PAR interception to measure LAI requires knowledge of leaf angles (O'Leary and Donaldson, 2000). O'Leary and Donaldson (2000) also noted that contemporary models of sugarcane have not been designed to simulate cultivar PAR interception differences with respect to LAI, rather they have mainly dealt with phenological differences including tiller number as described by Inman-Bamber (1994b). There is a need to investigate ways to model different cultivars of sugarcane that are known to exhibit different leaf angles that theoretically should have different PAR interception characteristics. Knowledge of this should lead to more accurate models of LAI and PAR interception in sugarcane.

An accurate model of canopy development is a pre-requisite for accurately predicting sugarcane growth, water use and yield. Canopy development is regulated by air temperature as dictated by locality and crop starting time. Field trials done at Pongola to improve understanding and modelling of canopy development showed that base temperature for canopy development is higher than previously thought and that the value is variety specific. Varieties NCo376 and N25 had a base temperature of 16 °C, while N16 had 18 °C (Anon, 1999). Therefore there is a need to determine the base temperatures of different varieties for incorporation into CANEGRO canopy development model.

O'Leary (2000) noted that most of the work on CANEGRO has been mainly on dry matter partitioning and limited work has been undertaken to specifically study the leaf component of canopy development. Ritchie and NeSmith (1991) made similar observations on other models.

Most work on CANEGRO validation was done on variety NCo376 in South Africa based on rain-fed data (Inman-Bamber, 1991a, 1994b; O'Leary, 2000). The model has been tested on sugarcane variety N12 (Inman-Bamber, 1994b). There are new varieties released in South Africa for rain-fed and irrigated conditions and these are replacing NCo376. CANEGRO model's inability to simulate other varieties is a major weakness (O'Leary, 2000). O'Leary (2000) noted that to simulate other undefined varieties users are required to supply the necessary genetic coefficients which can be time consuming to determine. The required variety specific parameters have not been clearly specified in any of the model's documentation. This should therefore be a priority for model developers. O'Leary and Kiker (2000) noted that defining different varieties is a problem in CANEGRO. The number of parameters that describe different varieties is very low and more parameters need to be added. The greatest need now is to describe how one can determine CANEGRO parameters for local varieties (O' Leary and Kiker, 2000). Keating *et al.* (1999) noted that genotype variation should be addressed through genotype specific parameters for canopy development. Inman-Bamber (1994b), White (1998) and Cock (2001) noted that a better understanding of canopy development could provide a basis for variety improvement.

2.8 CANEGRO canopy model description

2.8.1 Introduction

Various components of the sugarcane production system have been combined in a simulation model, CANEGRO. This mechanistic model describes some environmental, physiological and managerial features of the agricultural sugarcane production system. Bezuidenhout, (2000) described the environmental aspects of the CANEGRO model. The CANEGRO model is the most comprehensive sugarcane model calibrated and validated under South African conditions (Inman-Bamber, 1995, Bezuidenhout, 2000). It has been included as the sugarcane model for A Decision Support System for Agrotechnology Transfer (DSSAT) by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) and is used in various other sugarcane production regions in the world. Because of the complexity of the sugarcane production system, the CANEGRO model is not static and future refinements are anticipated.

The model is based on research from many crop, climatic and soil aspects. Some work was conducted on other crops and was later adapted for sugarcane. Other work was specifically conducted on sugarcane and often included different sugarcane cultivars and managerial scenarios. Because of the complexity of the system, experiments were designed to concentrate on certain aspects of the system. Individual experiments could therefore only give limited explanations of the system and in order to obtain a more comprehensive mechanistic model, results from many experiments were finally integrated through a computer programme.

2.8.2 Tiller population

Tiller density or population (n_{pop} in tillers ha^{-1}) is an important crop variable that is simulated by the CANEGRO model. It is later used to determine the amount of PAR that was intercepted by the crop, which is an important factor in determining photosynthesis and transpiration.

Some agricultural practices and biological processes can influence tiller population. Planting and harvesting practices like row spacing and planting density (e.g. Kanwar and Sharma, 1974) and mechanical harvesting and in-field haulage (e.g. Cochran and Richaud, 1980) influence tiller population. Three biological processes in sugarcane influence tiller population. Those are (1) the germination and emergence of primary tillers, (2) the natural process of underground branching and emergence of secondary and higher order tillers and

(3) tiller senescence. Under suitable growing conditions a typical commercial crop's tiller population will increase rapidly, which will then be followed by a phase of tiller senescence before the population becomes more stable.

Rostron (1972) found that tiller numbers could be correlated with cumulative heat units. Inman-Bamber (1994b) also noted that tillering rates, which is the rate at which underground branching occurs, could be mathematically linked to leaf emergence rates. Inman-Bamber (1994b) concluded that heat units with a base temperature of 16 °C produced the best results when compared with observed tiller populations. Tiller population was subsequently calculated by making use of a differential equation (Bezuidenhout, 2000).

$$n_{pop}(t) = n_{pop}(t-1) + \Delta_{pop} \qquad 2.3$$

where t is time in days and Δ_{pop} (tillers ha^{-1}day^{-1}) is the change in the tiller population since the previous day.

The simulated crop's population reaches a peak at about 500 °C day (base 16 °C). It was assumed that tillers exceeding the population of 3×10^5 tillers ha^{-1} would be small enough to be ignored (Inman-Bamber and Kiker, 1997). Four ΣHU_{16} intervals were identified to calculate Δ_{pop}, those were $\Sigma HU_{16} \in$ (0, 600 °C day), [600, 1500 °C day], (1500, 2000 °C day) and [2000, ∞ °C day). For the intervals $\Sigma HU_{16} \in$ [0, 600 °C day] and $\Sigma HU_{16} \in$ (600, 1500 °C day) the derivative of a 2nd order polynomial was used (Inman-Bamber and Kiker, 1997).

$$\Delta_{pop} = \left(1000 \times \frac{1.4}{z_{row}}\right)\left(p_1^{(cul)} + 2p_2^{(cul)}\Sigma HU_{16}\right)\left(HU_{16}\right) for \quad \left|\Sigma HU_{16} \le 1500°C\right. \qquad 2.4$$

where z_{row} (m) is the row spacing, $p_i^{(cul)}$ are cultivar specific polynomial coefficients (see Table 2.1) and HU_{16} is the heat units for the current day (°C day).

Inman-Bamber (1991a) noted that a mature sugarcane crop would have a predictable tiller population. These populations differ among cultivars, as summarised in Table 2.2. Although it was later considered that seasonal effects play a role in mature tiller populations (Inman-Bamber, 1994a), the CANEGRO model assumes a fixed mature tiller population. Tiller senescence would slow down after 1500 °C day and a linear decline towards the mature tiller population was maintained in the interval $\Sigma HU_{16} \in$ (1500, 2000 °C day). The population is kept constant after 2000 °C day for the rest of the duration of the crop (Bezuidenhout, 2000).

Table 2.1 Second order polynomial coefficients that were used to calculate Δ_{pop} for different cultivars in the intervals $\Sigma HU_{16} \in (0 - 600°C\times d)$ and $\Sigma HU_{16} \in [600 \text{ to } 1500°C\times d]$ (Inman-Bamber and Kiker, 1997)

	$\Sigma HU_{16} \in$ (0 to 600°$C\times d$)		$\Sigma HU_{16} \in$ [600 to 1500°$C\times d$]	
	p_1	p_2	p_1	p_2
Nco376	1.8260	-0.00201	-0.9902	3.282×10^{-4}
N12	0.01365	35.6594	3.689×10^{-3}	-7.260×10^{-6}
N14	-44.7707	40.5385	4.944×10^{-3}	-1.080×10^{-5}
R570	-38.4800	0.3190	-2.253×10^{-9}	1.019×10^{-11}

Because tillering is a continuous process for certain duration of the crop, the CANEGRO model accounted for inhomogeneous tillers by simulating up to thirty cohort groups while the crop is still in its developmental stages. Once the crop reaches its mature tiller population, cohort groups are combined into one group of homogenous tillers. Van Dillewijn (1952) noted that higher order tillers differ in vegetative composition to the primary tillers. Although limited data exist to investigate these differences it could be anticipated that future refinements to the model could include this issue.

The simulation of tiller population is based on empirically fitted polynomial equations and does not follow a mechanistic approach. The absence of a mathematical description of the three biological processes that influence tiller population limits the model's ability to simulate different planting and harvesting practices, like high density and double stick planting, ratooning and in-field mechanisation. The CANEGRO model will therefore enhance its functionality if future versions could simulate variety differences in tiller emergence, tillering and tiller senescence in a more mechanistic way.

Table 2.2 Mature tiller populations for different cultivars (adapted from Bezuidenhout, 2000)

Cultivar	**Mature tiller population** (tillers ha^{-1})
NCo376	133 000
N12	150 000
N14	120 000
R570	80 000

2.8.3 Leaf emergence and development

2.8.3.1 Leaf emergence

Under water stress free conditions, leaves will emerge according to a defined phyllochron interval (Inman-Bamber, 1994b). A phyllochron interval, expressed in °C day, is a specific amount of heat units that need to lapse before the next leaf on a tiller will emerge. Inman-Bamber (1994b) calculated the phyllochron interval on heat units with base 10 *°C* and determined a fixed phyllochron interval for the first 14 leaves (ξ_1) and another for leaves emerging thereafter (ξ_2). This is generally referred to as the broken stick equation. Van Antwerpen (1998) noted that higher biomass allocation rates to the rooting system could be one of the reasons for a change in the phyllochron interval after the 14th leaf.

$$n_{leaf} = \begin{cases} 1 + \dfrac{\Sigma HU^{(1)}_{10} - \Sigma HU_{10}}{\xi_1} & for \left| \ \Sigma HU^{(1)}_{10} - \Sigma HU_{10} \le 13\xi_1 \right. \\ 15 + \dfrac{\Sigma HU^{(2)}_{10} - \Sigma HU_{10}}{\xi_2} & for \left| \ \Sigma HU^{(1)}_{10} - \Sigma HU_{10} > 13\xi_1 \right. \end{cases} \qquad 2.5$$

where n_{leaf} is the number of leaves per stalk, $\Sigma HU^{(1)}_{10}$ is the accumulated heat units since the emergence of the tiller, and $\Sigma HU^{(2)}_{10}$ is the accumulated heat units since n_{leaf} reached a value of 14. Table 2.3 reflects different phyllochron intervals for different cultivars.

The senescence of green leaves in the CANEGRO model was based on NCo376 and was assumed that this cultivar would never have more than 12 green leaves at any stage.

2.8.3.2 Leaf development

Inman-Bamber (1994b) found the daily leaf elongation rate (*E*), expressed in mm day^{-1}, to be dependent on air temperature. A linear function was fitted on hourly-recorded leaf elongation data to determine a relationship with the mean daily temperature ($\bar{T}$ *in* °C day).

$$E = 24\times\left(-1.77 + 0.176\overline{T} \pm 0.45\right) \qquad 2.6$$

In the model it is assumed that no more than 4 leaves can expand simultaneously. Older leaves stop expanding once they reach a maximum allowable blade area. The maximum allowable blade area ($A_{max(j)}$ in cm^2) for the j^{th} sequential leaf since emergence is assumed to be leaf number and cultivar specific (Inman-Bamber and Kiker, 1997). Eq. 2.7 reflects the calculation of $A_{max(j)}$ for the NCo376 cultivar.

$$A_{max(j)} = \begin{cases} -20.8 + 27.2j & for|j \leq 15 \\ 387.2 & for|j > 15 \end{cases} \qquad 2.7$$

2.8.3.3 Leaf area index and PAR interception

The fraction of PAR intercepted by the crop is determined by the LAI. LAI is a measure of the crop's canopy and describes the relative collective area of foliage over all the tillers in the crop. Two parameters, the number of tillers and the total leaf area per tiller therefore determine the PAR interception ability of the canopy.

Leaf area index (LAI in cm^{2}cm^{-2}) is the total green leaf area per unit land surface. Leaf area index incorporates all the tillers on a unit surface and thereby represents characteristics about the crop as a whole, irrespective of the various states of different tillers. LAI can be calculated from the mean leaf area per tiller, $\overline{LA}$ (cm^2), and tiller population, n_{pop} (tillers ha^{-1}).

$$LAI = \overline{LA} \times n_{pop} \times 10^{-8} \qquad 2.8$$

Inman-Bamber (1991a) explained that dead leaves, which are not inclusive of LAI, would continue to shade the soil and therefore included this into the soil evaporation model (Eq. 2.8). The total leaf area index of dead and green leaves; LAI_{tot} (cm^2 cm^{-2}) was calculated by accumulating $A_{max(j)}$ over the different simulated cohort groups. This approach does not account for leaf rolling and shrinking that take place when leaves die (Inman-Bamber and Kiker, 1997).

$$LAI_{tot} = LAI + \sum_{k=1}^{K}\sum_{j=1}^{J_k} A_{\max(j)} \qquad 2.9$$

where K is the number of cohort groups in the CANEGRO model and J_k is the number of dead leaves per tiller in the k^{th} cohort group.

Table 2.3 Phyllochron intervals for different cultivars (Inman-Bamber, 1994b; Inman-Bamber and Kiker, 1997)

Cultivar	ξ_1 (°C.day)	ξ_2 (°C.day)
N14	109	169
N12	118	200
NCo376	109	169

Bouman *et al.* (1992) highlighted the importance of knowing the proportion of ground that was shaded by the crop. This property can be used to determine PAR interception and photosynthesis. By making use of LAI Inman-Bamber (1994b) calculated the fraction of *PAR* that was intercepted by the crop. This is known as the PAR interception of the canopy (L_i) and is calculated by making use of Beer's law.

$$L_i = 1 - e^{-ki \cdot LAI} \qquad 2.10$$

where *ki* is the extinction coefficient, which reflects properties of the canopy structure and time of the day.

Muchow *et al.* (1982) suggested that the value for *ki* changes during the developmental stages of the crop. In the CANEGRO model *ki* varies from 0.58 to 0.84 and is expressed as a function of the number of leaves in the first cohort group ($n_{leaf(1)}$).

$$ki = \begin{cases} 0.58 + 0.26\dfrac{n_{leaf(1)}}{20} & for|n_{leaf(1)} \leq 20 \\ 0.84 & for|\ n_{leaf(1)} > 20 \end{cases} \qquad 2.11$$

2.8.4 Stalk height and canopy height

In the CANEGRO model stalk height was assumed to increase at a rate of 16 % of daily leaf elongation. Stalk height is calculated for each tiller cohort group. Inman-Bamber (1994a) noted that stalk growth would slow down once the tiller reached maturity. Van Dillewijn (1952) also pointed out that tillers of a higher order (i.e. later emerging tillers) would elongate faster than primary tillers. It was further noted that at a distinct stage in the crop, tillering would slow down and stalks would elongate more rapidly. These characteristics have not been considered for the CANEGRO model yet. They could form part of future model refinements.

Canopy height was calculated by assuming a 30.2° angle between the stalk and the tip of the highest leaf.

$$z_{can} = z_{stk} + \cos(30.2°) \times l \tag{2.12}$$

where l (cm) is the length of the longest leaf in the first tiller cohort group.

2.8.5 Tiller model

It was noted that the CANEGRO model does not mechanistically simulate the following three biological processes: (1) primary tiller germination and emergence, (2) tillering and (3) tiller senescence. This restricted the model's applicability as the model was unable to simulate differences between planted and ratoon crops, mechanically harvested and hand harvested crops and to some extent different planting densities (Bezuidenhout, 2000).

Five crop phases were subsequently defined according to phenological development; pre-germination phase (crop initiation to germination of the first bud); pre-emergence phase (bud germination to emergence of the first shoot); primary tiller emergence phase (first shoot emergence to last primary shoot emergence); secondary tiller emergence phase (last primary shoot emergence to first tiller senescence) and tiller senescence phase (first tiller senescence to harvest).

Tillering results in a stool of upright stalks containing one primary tiller and various numbers of higher order secondary and tertiary tillers. This process was assumed to be continuous under no resource limitations. Van Dillewijn (1952) identified PAR and day length as the most important driving factors for tillering, while air temperature was considered to be the second most important driving factor. It was specifically noted that tillering in sub-tropical regions, like in South Africa, could be particularly sensitive to low temperatures and more extreme day lengths. Inman-Bamber (1994b) noted that a base temperature of 16 °C could be used to simulate the response of tiller population to air temperature.

The tiller model assumed that the tillering phase initiates after the last primary tiller emerged above the ground. Similarly to the CANEGRO model (Inman-Bamber and Kiker, 1997), it also assumed those younger tillers would undergo senescence first, subsequently causing the tillering phase to terminate as soon as tiller senescence steps in. Van Dillewijn (1952) mentioned two fairly distinct sub-phases during tillering; (1) a sub-phase of profuse tillering and (2) a sub-phase with a decline in tillering and more distinctive stalk elongation due to PAR competition.

Observations during the sub-phase of profuse tillering indicate that the first secondary tiller would emerge above the ground after six leaves on the primary tiller have emerged. It was assumed that a fixed period is required for the production and emergence of a higher order tiller under no PAR limitations. This period was defined as the telomechron interval (°C day). The telomechron interval was derived from the word *telome*, which refers to a terminal branch of a vascular plant (Gray, 1976), and is analogous to the phyllochron interval. This model simulates a constant maximum relative tillering rate in HU_{16} when no light limitations apply (n_ω in tillers tiller^{-1}°C^{-1}d^{-1}). ω is the thermal time (°C.day) required to produce a tiller using a base temperature of 16 °C.

$$n_\omega = \frac{1}{\omega} \qquad 2.13$$

The above conditions imply an exponential increase in tiller population. The population increment per HU_{16} (Δn_{pop} in tillers ha^{-1}) for this sub-phase can therefore be calculated using (Sanches *et al.*, 1988):

$$\Delta n_{pop} = n_\omega \times e^{n_\omega (\Sigma HU_{16} + i)} \qquad 2.14$$

where ΣHU_{16} (°C day) is the thermal crop age and i is an empirically fitted constant.

The second sub-phase, which is when PAR competition exists and stalk elongation receives preference, was driven by the PAR availability to the individual tiller. The model uses L_i and a s' (stool diameter correction factor) to determine the amount of competition that exists in the crop. The stool diameter correction factor compensates for recently planted crops to utilise inter-row PAR less efficiently than later ratoon crops. This factor asymptotically approaches unity for later ratoons. The relative tillering rate under PAR competitive conditions (n' in tillers tiller^{-1} °C^{-1} day^{-1}), with $n' \leq n_\omega$, is subsequently calculated as a function of L_i and s' (Bezuidenhout, 2000).

Tiller population during the tillering phase at future thermal time $t+1$ is calculated from that at thermal time t:

$$n_{pop}(t+1) = n_{pop}(t) + \Delta n_{pop} \qquad 2.15$$

Where

$$\Delta n_{pop} = n' \times n_{pop}(t) \qquad 2.16$$

And

$$n' = f(L_i, s') \leq n_\omega \qquad 2.17$$

and t is thermal time (HU_{16} in °C day).

For this model, tiller senescence is driven by the availability of PAR to the individual tiller, which is expressed by LAI and s'. This phase continues until harvest and initiates when the youngest tiller in the crop has a leaf area (LA in cm^2) that is lower than a calculated minimum sustainable leaf area per tiller (LA'_{min} in cm^2), expressed in terms of LAI and s'. All tillers that become unsustainable are immediately removed from the crop.

2.8.6 Discussion

The above description of the model highlights the weakness of the model in describing variety parameters. Where these are described, it is not in sufficient detail to predict variety differences in canopy growth and development. The tillering process was described as occurring during a fixed time interval while varieties are likely to show differences in the tillering rates. This could result in the tiller development stages being different for different varieties. The leaf emergence of varieties was shown to be different (Inman-Bamber, 1994b) but even within the phyllochron 1 and 2 phases of development, differences are likely to occur for a particular variety and within varieties. Other methods of describing leaf emergence may need to be investigated for the model to accurately predict leaf emergence of varieties and also predict variety differences in leaf emergence. The ability of the model to predict leaf emergence is critical as leaves intercept PAR and are the photosynthetic factory. Therefore the prediction of intercepted PAR will depend on accurate prediction of leaf emergence and leaf area. Tillers or stalks are the major sinks. The ability of the model to adequately predict their growth and development and variety differences is important for predicting the yield of the crop and also modelling variety differences in yield.

This study aims to determine the variety differences in canopy growth and development of four varieties (ZN6, ZN7, N14 and Nco376) grown in the South East Lowveld of Zimbabwe, determine possible physiological parameters that could be used to model the variety differences in canopy development and evaluate the improved and current CANEGRO canopy models for their ability to predict variety differences in canopy growth and development.

Chapter 3 MATERIAL AND METHODS

3.1 Experimental sites

Data was collected from experiments at the Zimbabwe Sugar Association Experiment Station (ZSAES) that is located on sandy loam soils. ZSAES is 430 m above sea level at a latitude of 21°01' S and longitude 28°38' E (Anon, 1998).

Experimental sites were located on N1a block (experiment 1), S1 block (experiment 3), N1b block (experiment 4) and C10 (experiment 2). N1a, N1b and S1 blocks were furrow irrigated while C10 block was irrigated with overhead sprinklers. Canopy growth and development data was collected from Experiments 1 and 2 (October 19 2001 to October 19 2002) while data on emergence of planted eyes was collected from experiments 3 (from 20 March 2002 to 20 March 2003) and 4 (from July 6 2002 to 20 March 2003)..

3.1.1 Meteorological data (1970-2001)

The South East Lowveld of Zimbabwe is characterized by hot and dry weather with high A-pan evaporation (Fig. 3.1). The period May to September has very little rainfall. The summer months (September to March) are characterized by higher air temperature, higher A-pan evaporation, faster wind speeds and erratic rainfall.

3.1.2 Weather data Collection

Weather data were collected throughout the cropping season from an automatic weather station (AWS) situated at ZSAES and from the manual station located next to the AWS. Block C10 is located 50 m from the AWS, N1 800 m and S1 1000 m. The weather variables collected were air temperature (minimum and maximum), soil temperature (from May to August), daily rainfall, wind speed, relative humidity, atmospheric water vapour pressure, solar irradiance and open pan evaporation (from the class A pan).

3.1.3 Soil analysis of block N1

The soil from each replication was sampled on the 18th of October 2001 and analysed on the 30th of October 2001. A mechanical and chemical analysis was done on the soil samples. Soil colour was judged visually while the soil texture was determined from mechanical analysis (Tables 3.1 and 3.2). Soil texture class was read from the soil texture triangle (Matibiri, 1998).

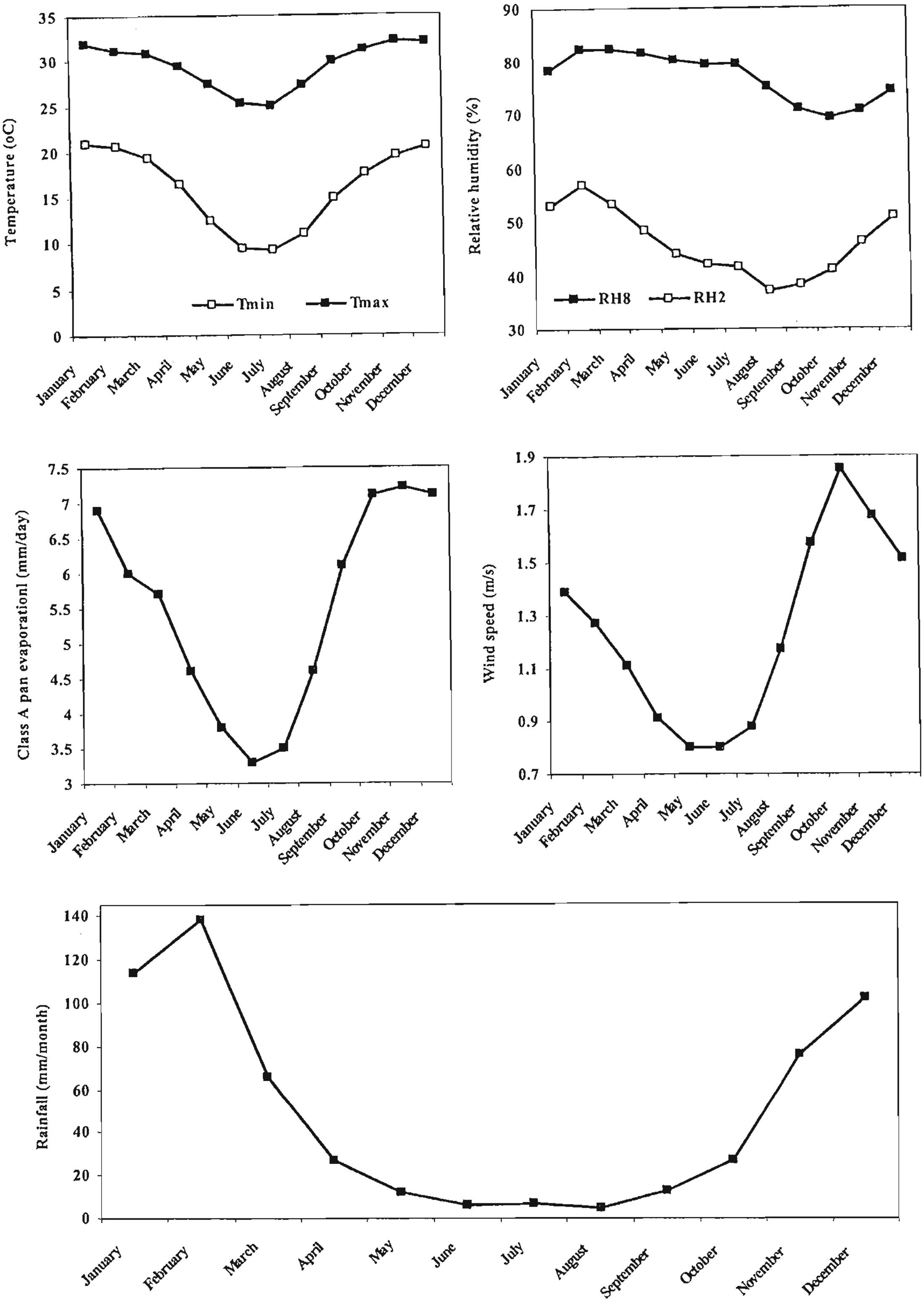


Fig. 3.1 The long term means (1970-2001) for minimum and maximum air temperature °C, relative humidity (%), A-pan evaporation (mm/day), wind speed (m/s) and rainfall (mm/month) for ZSAES weather station

Table 3.1: Soil colour, soil texture class, clay %, silt % and sand % of soil samples from replications 1, 2, 3, 4, 5 in experiment 1 located in block N1

Replication	Soil colour	Soil Texture class	Clay %	Silt %	Sand %
1	Brown	Sandy Loam	18	6	76
2	Brown	Sandy Loam	18	4	78
3	Brown	Sandy Loam	16	6	78
4	Brown	Sandy Loam	14	6	80
5	Brown	Sandy Loam	16	6	78

3.1.4 Experimental designs and layout

Experimental plots in experiments 1, 2 and 4 were arranged in a randomized block design while experiment 3 was not replicated. Experiments 1 and 2 had four varieties by five replications (Fig. 3.2) while experiment 3 had four varieties by three replications. The rows were spaced 1,5 m apart. The randomization was done using Plant Breeding Variety Trials Analysis System (PBVTAS) programme (McLaren, 1990). The plot layouts were done as described by Petersen (1994) and Little and Hills (1978).

3.1.4.1 Experiments 1 and 2

The plot sizes were 13 rows by 10 m long spaced 1,5 m apart (Fig. 3.3). Rows 1 to 5 were used for pre-harvest destructive sampling while row 13 was used for leaf emergence records. Rows 7 to 11 will be the nett plot area. Half a meter were discarded on either side of rows 7 to 11 at harvest to leave a nett plot of 5 rows by 9 m spaced 1,5 m apart. The nett plot areas were harvested at 12 months age and cane weights, stalk numbers, stalk lengths and diameters, internodes per stalk and cane quality measurements were done.

Table 3.2: pH (based on Calcium Chloride method), conductivity (1:5 solution), P_2O_5 (parts per million resin extract), Potassium, Calcium, Magnesium and Sodium (milli equivalents %) of soil samples from replications 1, 2, 3, 4 and 5 located in block N1

Rep	pH	Conductivity	P_2O_5 (ppm)	K (m.e.%)	Ca (m.e.%)	Mg (m.e.%)	Na (m.e.%)
1	6,79	206	41	0,25	12,2	2,2	0,37
2	6,55	105	23	0,20	8,7	2,1	0,36
3	5,43	52	16	0,20	7,5	2,0	0,20
4	5,48	41	36	0,17	7,6	1,9	0,17
5	5,49	39	33	0,18	7,7	2,0	0,18

Irrigation feeder canal

4 1	3 3	2 2	1 4
8 1	7 4	6 3	5 2
12 4	11 2	10 3	9 1
16 4	15 1	14 3	13 2
20 2	19 3	18 4	17 1

Fig. 3.2 Layout for experiments 1 and 2 located in N1-a and C10 blocks. The top left number represents the plot number while the bottom right number represents the variety number. Varieties 1, 2, 3 and 4 represent ZN6, ZN7, N14 and NCo376 respectively. Plots 1-4, 5-8, 9-12, 13-16 and 17–20 represent first, second, third, fourth and fifth replicates respectively

3.1.4.2 Experiments 3 and 4

For experiment 3, the plot sizes were variable and spaced 1,5 m apart (Fig 3.4) while experiment 4 was 10 rows by 17 metres (Fig. 3.5). The number of emerged eyes was counted for each plot from Monday to Saturday until more than 50% of the eyes had emerged in all plots.

13	12	11	10	9	8	7	6	5	4	3	2	Row1

Fig. 3.3 Row layout in a plot in experiment 1 located in N1 block. Rows 1 to 5 were used for destructive sampling. Row 13 was used for collecting data on leaf emergence while rows 7 to 11 were used as nett plot for harvesting at 12 months age

Tail drain

N14 (11 rows, 13 m long)	ZN7 (10 rows, 13 m long)	ZN6 (10 rows, 13 m long)
NCo376 (11 rows, 8 m long)		

Fig. 3.4 Plot layout in experiment 2 established in S1 block

3.1.5 Sampling Procedure and Sampling Dates

The sampling units were pre-determined and marked with wooden pegs in the experimental area. The sampling area consisted of one running metre in the cane row with one metre guard area on all sides of the sampled area (Fig. 3.6 and 3.7). All the cane in the one metre was cut and taken to a shed where all the measurements were done. Sampling was done every 14 days until the crop was 12 months old (Table 3.3). Samples were taken every Wednesday. Sampling was done from 05h00. During the first samplings, a hand knife was used to cut the cane in the one metre row to avoid uprooting the setts with a cane knife. When the cane was established a sharp cane knife was used to cut the sample.

1 2	2 1	3 4	4 3
5 4	6 3	7 2	8 1
9 3	10 4	11 1	12 2

Fig. 3.5 Layout for experiment 4 located in N1-b block. The top left number represents the plot number while the bottom right number represents the variety number. Varieties 1, 2, 3 and 4 represent ZN6, ZN7, N14 and NCo376 respectively. Plots 1-4, 5-8 and 9-12 represent first, second and third replicates respectively

Row 1	Row 2	Row 3	Row 4
1m discard area	1m sampling area	1m discard area	1m sampling area
1m sampling area	1m discard area	1m sampling area	1m discard area
1m discard area	1m sampling area	1m discard area	1m sampling area

Fig. 3.6 The 0,5 m guard on either side of a 1 m sampling area on the cane row. Wooden pegs were placed on either side of the 1 m sampling row length before sampling

3.1.6 Crop management

The crops were planted using two cane setts laid side by side in the bottom of the planting furrows spaced 1,5 m apart. Single superphosphate fertilizer was applied in the furrow before planting at 100 kg per hectare P_2O_5. Potassium was applied as muriate of potash at 60 kg per hectare K_2O after 4 weeks from emergence. Nitrogen was applied as ammonium nitrate at 140 kg N per hectare with 60 kg N per hectare applied at 4 weeks after emergence and 80 kg per hectare applied at 8 weeks after emergence. Hand weeding was as frequent as required to control the weeds. Smut rouging and inspection for other diseases was done once every month. Irrigation was scheduled using evaporation data from a United States Weather Bureau Class A (A-pan) located close to the AWS. Water was applied at 50% depletion of total available water (TAM) to 1,0 m soil depth. TAM is soil water content at field capacity minus soil water content at wilting point.

r1	r2	r3	r4	r5	r6	r7	r8
	6		16		26		37
1		11		21		31	
	7		17		27		38
2		12		22		32	
	8		18		28		39
3		13		23		34	
	9		19		29		40
4		14		24		35	
	10		20		30		41
5		15		25		36	

Fig. 3.7 The predetermined sampling position for a plot in experiment 1 in N1a block. Each box marked with a number represents a sampling unit of 1 metre length and is surrounded by guard rows on all sides. There was no interference between sampling positions diagonally opposite each other.

Table 3.3. Scheduled sampling dates for destructive samples from experiment 1 located in block N1a

22 November 2001	13 February 2002	8 May 2002	31 July 2002
6 December 2001	27 February 2002	22 May 2002	14 August 2002
19 December 2001	13 March 2002	5 June 2002	28 August 2002
2 January 2002	27 March 2002	19 June 2002	11 September 2002
16 January 2002	10 April 2002	3 July 2002	25 September 2002
30 January 2002	24 April 2002	17 July 2002	9 October 2002
			23 October 2002

3.2 Instruments used

3.2.1 Delta-T leaf area meter

The Delta-T leaf area meter (Delta-T, Cambridge, UK) was used to measure leaf area. The Delta-T area measurement system (Fig. 3.8) measures the area of any object, image or silhouette that can be seen in high contrast by a standard television (TV) camera. The camera scans the object, line by line, to build up a picture, taking 1/25 seconds to complete two interlaced scans. The area meter times the parts of the scan when it is detected and scans these over the measurement period. The measurement period is adjustable. The sum of the scans is a measure of the object area and can be adjusted for calibration using an object of known area. A standard TV monitor is used to display the results. The leaves were fed through the conveyer system. The conveyer belt of the area meter system is designed to stand on top of the light box. It makes for easier handling of objects that do not readily lie flat, automatic totaling of area measurements and continuous measurements. The conveyer is composed of two highly transparent belts mounted one above the other, on soft rubber O-rings on pairs of counter rotating rollers (Delta-T devices, User Manual, undated).

3.2.2 SunScan canopy analysis system

The SunScan canopy analysis system consist of a sunscan probe, beam fraction sensor and data collection terminal (Fig. 3.9). The SunScan probe has a light sensitive wand that is 1 metre long, containing 64 photodiodes equally spaced along its length. The probe handle contains batteries and electronics for converting the photodiode outputs into digital PAR readings, which are transferred to a data file via the RS232 link. The Beam Fraction Sensor (BFS) measures PAR levels in addition to the SunScan probe. It is used to monitor the PAR incident on the canopy at the same time as measurements beneath it. The BFS incorporates two photodiodes, one of which can be shaded from the direct solar beam by the shade ring. This allows the direct and diffuse components of PAR to be separated, which is necessary for the computation of LAI. To observe and store the readings from the SunScan probe, the data collection terminal (a Psion Workabout) is used. The work-about is a lightweight palm top mini-computer, a robust field unit with a full alphabetic keyboard for the annotation of readings with a removable flashcard that can be used for data storage and transfer (Potter *et al.*, 1996).

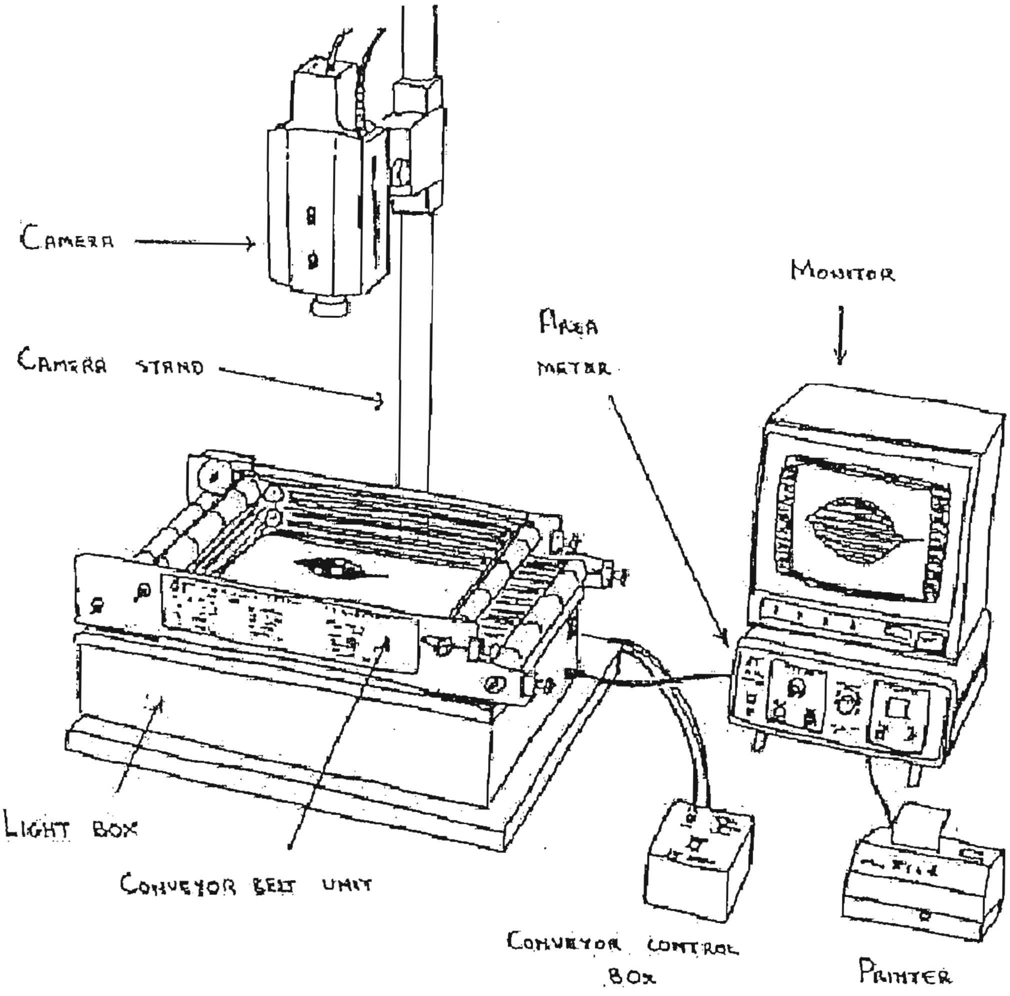
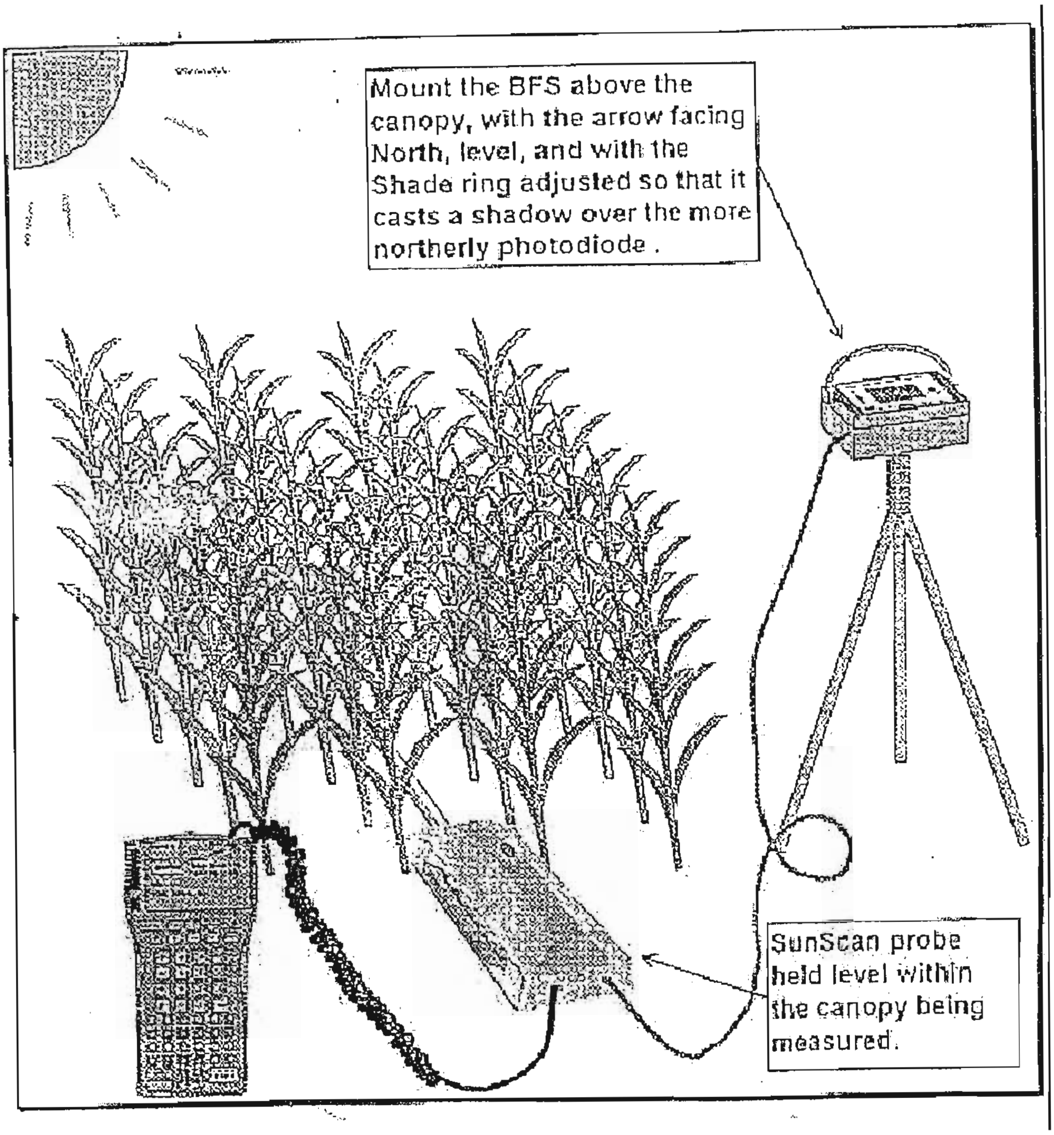


Fig. 3.8 The Delta-T leaf area meter showing the light box, conveyor belt, camera, area meter and monitor (adapted from Delta-T leaf area meter, User Manual, undated)



Mount the BFS above the canopy, with the arrow facing North, level, and with the Shade ring adjusted so that it casts a shadow over the more northerly photodiode .

SunScan probe held level within the canopy being measured.

Fig. 3.9 The SunScan ceptometer with the Psion Workabout to the left, the SunScan probe in the middle and the beam fraction sensor to the right (adapted from Potter *et al.*, 1996)

3.3 Plant and canopy measurements

The sampling units were pre-determined in the experimental area and the sampling area. Data on tiller counts, tiller and stalk heights, internode numbers, leaf numbers and leaf area were collected from destructive samples. The following describes the procedures used to take the various plant measurements.

3.3.1 Tiller counts

The total number of tillers in the sample was counted at each sampling date. Dead tillers were not counted because when tiller senescence started, tillering would stop and therefore dead tillers could be calculated from the tiller senescence curves.

3.3.2 Tiller heights

The tiller heights were measured as the length from the base of the tiller up to the top most visible dewlap or leaf collar. Each tiller height was measured and recorded separately.

3.3.3 Stalk numbers, internode numbers and stalk heights

The tillers were trashed. Tillers with developed internodes were counted and recorded as stalks. The numbers of developed internodes were counted for every stalk. The stalk heights were measured from the base of the stalk to the natural breaking point. The natural breaking point of the stalk is the point from the base of the stalk where the cane top is easiest to break.

3.3.4 Canopy height

The canopy height was measured as the height from the ground at the base of the stalks to the top of the canopy at the center of the sampling unit before it was cut. The top of the canopy is the top of all the leaves in the crop canopy. A horizontal stick was used to mark the top of the canopy where the height was read on the plant height stick or measuring tape.

3.3.5 Leaf number

The total number of green (including emerging) leaves and dead leaves were counted in the sampled area. Fully emerged, emerging and dead leaves were recorded separately. Fully emerged leaves were those leaves that were fully expanded while emerging leaves were those that were not fully expanded and those still emerging. Dead leaves included those that were yellowing. The above was a destructive sampling. Five representative stalks were selected and tagged per plot. Counts of the number of green leaves on each stalk were done once every week on Mondays on the same plants.

3.3.6 Leaf area

A Delta-T leaf area meter borrowed from Chiredzi Research Station was used to measure the leaf area. This is a destructive method of measuring leaf area. Leaf area was measured on all green leaves using the Delta-T leaf area meter.

A five-stalk sample was taken from each variety and the leaf numbers were recorded. The leaf area of each leaf was measured using a Delta-T leaf area meter.

3.3.7 Leaf emergence

Five stalks were tagged per plot from which leaf emergence was recorded. A yellow plastic ribbon was used to tag the stalks. The tagged stalks were spaced 1 m apart with the first tiller located 4 m from the edge of the plot. A wooden plot peg was placed opposite the tagged plant to help with identification of the tagged plant. The date of emergence of new leaf tips were recorded from 06h00 on Monday, Tuesday, Wednesday, Thursday, Friday and Saturday of every week until the crop was harvested.

3.3.8 Leaf angles and ellipsoidal leaf angle distribution parameter (ELADP).

Five representative stalks per plot were selected and tagged using plastic ribbons. The leaf angles of all the leaves on the stalk were measured using a protractor once every two weeks. From the leaf angles, the number of leaves that were more than 45 degrees from the vertical and the number of leaves less than 45 degrees from the vertical were counted. ELADP was estimated from the Eq. 3.1 (Potter *et al*, 1996).

$$\mathrm{ELADP} = (\Pi \times N_h)/2N_v \qquad 3.1$$

Where factor $\Pi/2$ comes from the fact that the vertical leaves are distributed about the vertical axis, so for any light ray, some will be seen face on, and some edge on, N_h is the number of leaves with angles more than 45° from the vertical and N_v the number of leaves with angles less than 45° from the vertical.

3.3.9 PAR Interception

Photosynthetic Active Radiation (PAR, $\mu mols^{-1}m^{-2}$) was measured above and at the bottom of the crop canopy between 11 in the morning and 2 in the afternoon using a SunScan ceptometer. This instrument measures the photosynthetically active radiation (400 to 700 nm). The measurements at the bottom of the crop canopy were done at five positions in each plot. The probe handle was placed at the center of the interrow while the probe was placed from the centre of the interrow to the centre of the cane line with growing plants. The readings were taken on either side of the centre of the interrow in a diagonal format. The readings were taken on five consecutive positions using this format.

3.4 Data processing and calculations

Data collected was analyzed using MSTAT version 4-computer software programme to produce analysis of variance tables and table of means for the plant and canopy measurements for each experiment. Regression analysis was done using Microsoft Excel Analysis ToolPak.

3.4.1 Calculation of PAR and extinction coefficients

The PAR measurements above and below crop canopy were used to calculate the fraction of PAR intercepted.

$$\text{PAR\%} = (\text{above canopy PAR - below canopy PAR x 100})/\text{above canopy PAR} \qquad 3.2$$

The extinction coefficients (k) were calculated from Beer's Law formula

$$\text{PAR}_{intercepted} = 1\text{-e}^{-k.LAI} \qquad 3.3$$

where $\text{PAR}_{intercepted}$ = PAR interception calculated as PAR (%) (Eq. 3.2)
LAI = measured leaf area index
e = natural logarithm, with an approximate value of 2,71828.
Solving for k in Eq. 3.3 will calculate the extinction coefficient.

The calculations for PAR and extinction coefficients will be calculated for all the four varieties in the experiments at every time of sampling and PAR interception measurements. Extinction coefficients were determined from the fitted straight-line equation of a graph of LAI on the x-axis and natural log transformation transmitted PAR on the y-axis.

3.4.2 Calculation of leaf area index

Leaf area index (LAI) is the total green leaf area (one side only) per unit land surface area. LAI was calculated from the total measured leaf area per sample divided by 1,5 m^2 (the sampling area) based on fixed plant spacing. The sampling was done on one running metre on cane rows spaced at 1,5 metres.

3.4.3 Calculation of phyllochron 1 and 2 and phyllochron switch

A phyllochron is the interval, either on a calendar or thermal unit basis, between the emergences of successive leaves. Phyllochron interval is thermal time divided by the number of leaves. Data from the weather station were used to calculate the accumulated thermal time (degree days), using a base temperature of 10 °C (Eq. 2.1). A degree-day is the mean daily air temperature minus the base temperature. The rate at which new leaves are produced was calculated from thermal time divided by leaf number. Phyllochron switch was determined graphically as the leaf number where the R^2 for Phyllochron 1 and Phyllochron 2 were greatest representing a change in leaf appearance from phyllochron 1 to 2. The phyllochron 1 and 2 were determined for each variety after the determination of the phyllochron switch.

3.4.4 Tiller emergence and senescence rates and population curve.

The number of stalks/tillers produced between sampling intervals was used to calculate the daily stalk emergence rates from the number of stalks/tillers divided by number of days between sampling that is fixed at 14 days. The stalk emergence rates were also calculated against thermal time, number of stalks/tillers divided by thermal time calculated using a base temperature of 16 °C. A proposed broken stick model was used to determine tiller emergence and senescence rates.

Data from the weather station was used to calculate the accumulated thermal time (Eq. 2.1). A stalk population curve will be determined from the stalk population per hectare versus thermal time for the four varieties in experiment 1.

3.4.5 Base temperatures

The base temperature for each variety was determined by a curve of air temperature against growth measurements and identifying the point on the curve where growth was close to zero. The base temperatures were done by regressing the parameters against accumulated thermal time calculated using different base temperatures. The temperature where the R^2 was greatest was assumed to be the base temperature. Base temperatures were determined for tiller population, tiller heights, canopy heights, stalk heights and internode numbers.

Chapter 4: VARIETY DIFFERENCES IN CANOPY GROWTH AND DEVELOPMENT

4.1 Introduction

The leaves and tillers are the major components of a sugarcane canopy. The leaves are the photosynthesis factories. The tillers support the leaves and form the major sink for photosynthates. Canopy development of varieties will deal with the development of leaf and tiller populations; tiller, stalk and canopy heights; internode numbers per stalk and green leaf numbers per plant. Rates of leaf population increase and decrease, tillering and tiller senescence rates will also be discussed. New proposals for modelling these processes are also discussed. Canopy growth will deal with tiller, stalk and canopy heights growth rates and internode numbers per stalk. The variety differences in growth and development will be discussed. Proposals for modelling these processes will be suggested. The aim of this chapter will be to determine the variety differences in canopy growth and development of sugarcane so as to improve their modelling. This should improve the identification of the stages of growth and development of the canopy and improve the identification of those critical stages of growth and development that distinguish varieties. The aim is also to identify the critical stages of development when variety selection can be targeted to be most effective.

4.2 Leaf population development

4.2.1 Green leaf numbers per hectare

The total number of green leaves in an area of 1,5 m^2 were counted at each sampling time. These were analysed and the trends in the development of leaf population in the varieties identified.

4.2.1.1 Total green leaves per hectare

There were three phases of development when total green leaf numbers were plotted against days after planting and accumulated thermal time calculated with a base temperature of 10 °C (Fig. 4.1). There was a rapid increase, a peak, followed by a decrease. The varieties reached peak green leaf population rapidly. The leaf population briefly stabilized at the peak before decreasing. The decrease phase continued until crop harvest. The varieties had different leaf increases and peaks. Varieties NCo376 and N14 had higher peak leaf population than ZN6 and ZN7. Variety ZN6 achieved its peak population later and ZN7 peaked earlier than NCo376 and N14. Variety ZN7, after achieving its peak leaf population had the least leaf population decline. Variety NCo376 had the highest leaf population while ZN7 had the least. High stalk population varieties (N14 and NCo376) had higher peak leaf populations than low stalk population varieties (ZN6 and ZN7).

4.2.1.2 Fully emerged green leaves per hectare

The fully emerged green leaves showed three phases, rapid increase and peak and decrease phases (Fig. 4.2). These phases were more pronounced on all varieties except ZN7. Variety ZN7 reached its peak and maintained a more stable leaf population than the other varieties. Variety ZN6 reached its peak leaf population later than N14 and NCo376. Variety NCo376 maintained the highest leaf population while ZN7 had the least.

4.2.1.3 Emerging green leaves per hectare

All varieties showed the three phases of emerging leaf population development, rapid increase, peak, and decrease phases (Fig. 4.3). Varieties ZN7, NCo376 and N14 had similar peak while ZN6 peaked later. After peak, ZN7 had a sharp decrease in leaf population followed by a gradual decrease. Varieties ZN6, N14 and NCo376 showed gradual leaf population decrease.

4.2.1.4 Dead leaves per hectare

The developmental phases of dead leaves showed increases that occurred in steps (Fig. 4.4). This trend was evident in all varieties. The low stalk population varieties (ZN6 and ZN7) showed a gradual increase in dead leaf population. Variety N14 and NCo376 showed a rapid increase in dead leaf population and developed the first step earlier than ZN6 and ZN7. After the first step, N14 had a lower increase in dead leaf population than NCo376. Higher stalk population varieties had more dead leaves than lower stalk population varieties. There were very few dead leaves in the younger crop. The start of the rapid increase in dead leaf numbers occurred around the same time as the peaks for total and emerging green leaf population (Figs. 4.1 and 4.3). This could mean that leaf senescence started after peak leaf population and also when leaf emergence started slowing down, probably during phyllochron 2 interval.

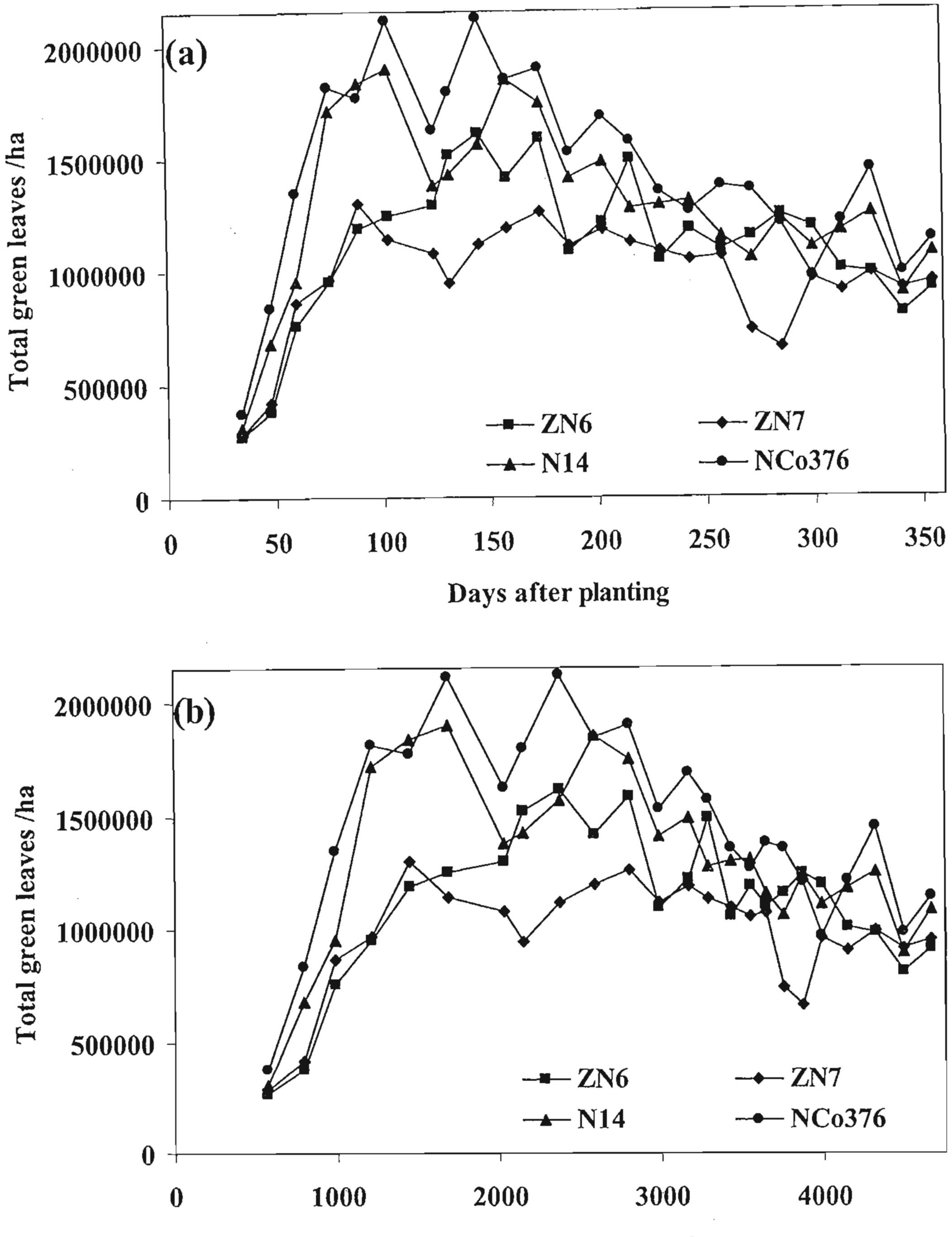


Fig. 4.1 The development of total green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 10 °C

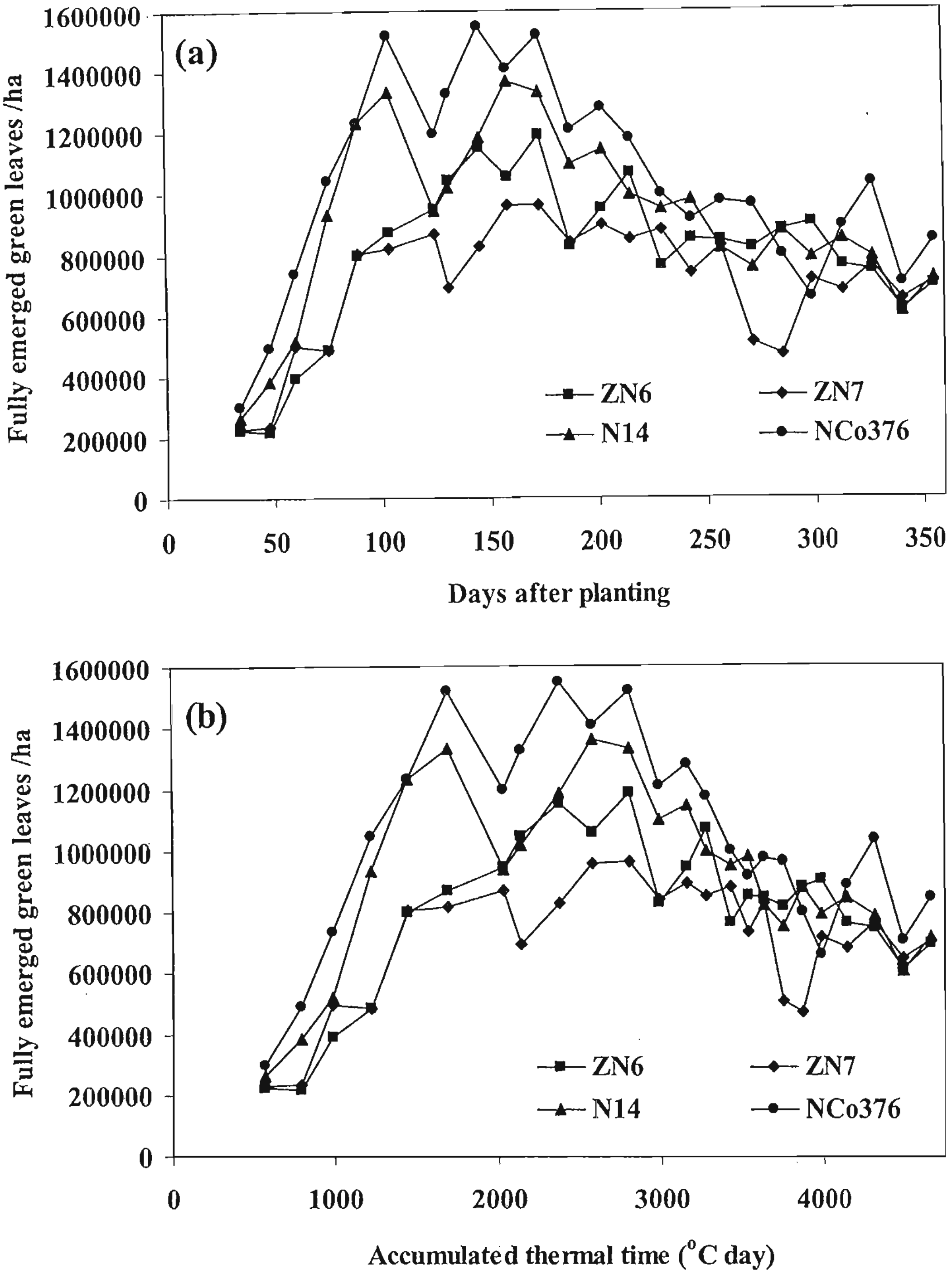
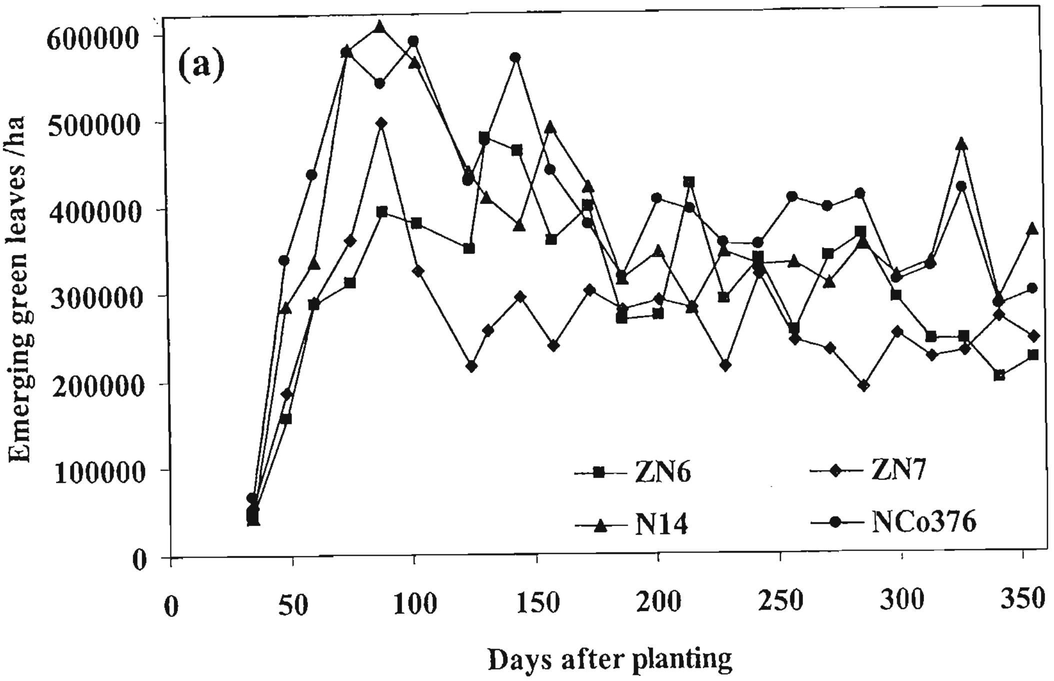


Fig. 4.2 The development of fully emerged green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 10 °C



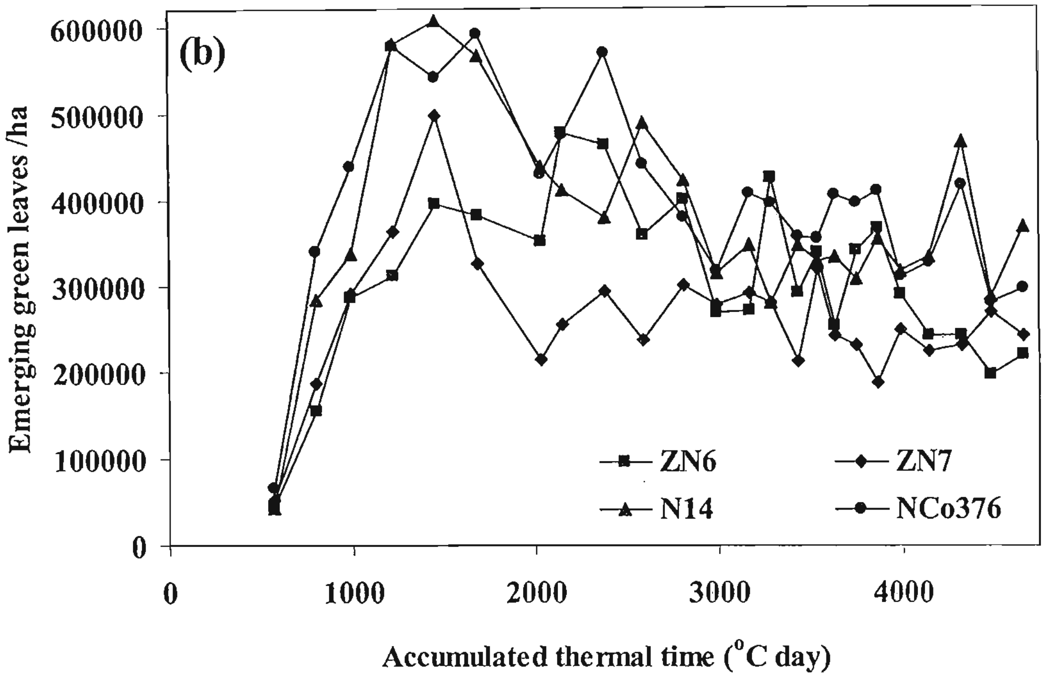
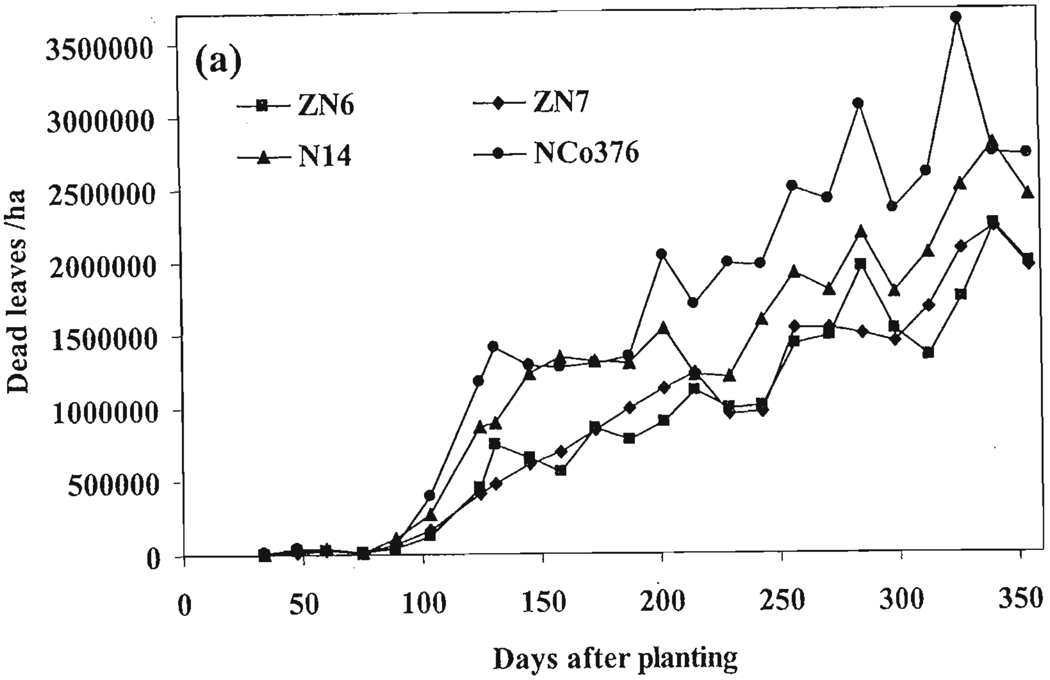


Fig. 4.3 The development of emerging green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 10 °C



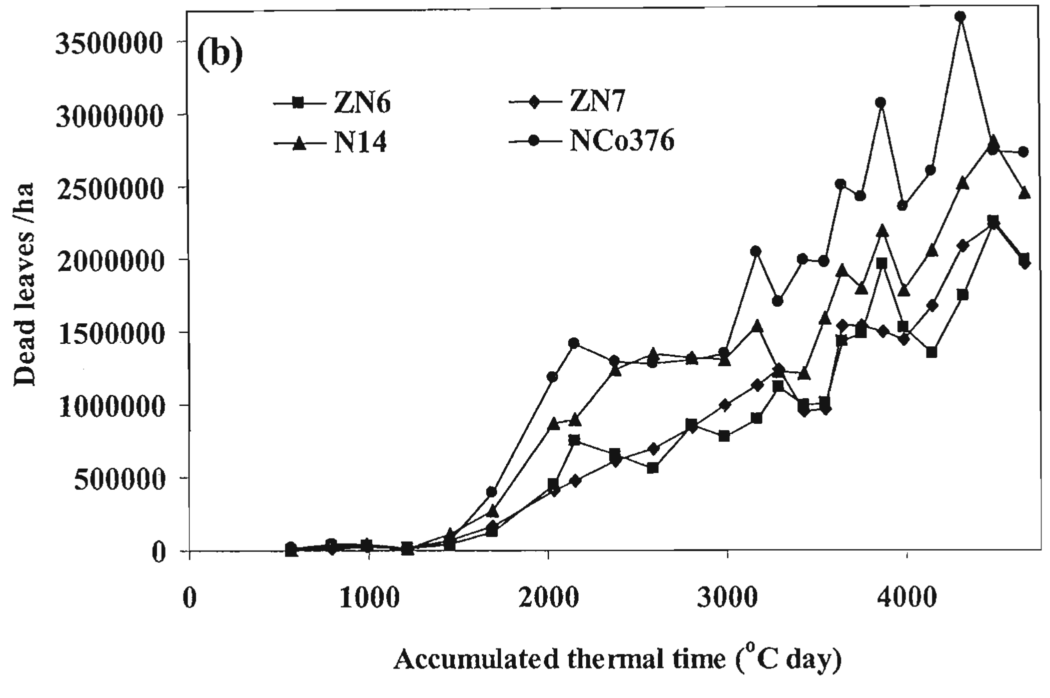


Fig. 4.4 The development of dead leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 10 °C

4.2.2 Broken Stick for modelling leaf population development

When data on leaf population were plotted against accumulated thermal time (TT10), two fitted straight lines corresponded rapid leaf population increase and leaf senescence phases (Figs 4.5, 4.6 and 4.7). High R^2 values were observed in the first phase of development for total, fully emerged and emerging green leaves per hectare. The second phase had lower R^2 values than the first phase and ZN7 had the least R^2 value. When a regression analysis was done, the data was highly significantly (P = 0,01) correlated to thermal time in the two phases of development (data not shown). The broken stick model could offer a method of modelling leaf population development. The break points for the varieties were different with varieties ZN6 and NCo376 breaking at same time while ZN7 and N14 had similar break points. The high R^2 values for the first phase may indicate that this phase was strongly driven by air temperature while the other factors could be driving the second phase. The factors that drive the decline in the second phase may need to be identified so that their effect can be minimized to maintain a high LAI and possibly increase yields. This aspect can also be useful during the variety selection, by selecting varieties with more green leaf numbers per stalk and a longer green leaf life expectancy.

4.2.2.1 Rates of leaf population increase and decrease

The coefficient of x of the line fit was taken as the rate of increase or decrease in leaf population. The varieties had different rates of green leaf increase and high leaf population varieties had higher rates than lower leaf population varieties in all the three categories. In the decline phase, NCo376 had the highest and ZN7 the least rates of decline (Figs 4.5, 4.6 and 4.7). Varieties with a lower rate of leaf population decrease are more desirable as they are likely to have a better balance of leaf emergence and leaf senescence.

4.2.2.2 Rates of increase in dead leaf population

A straight line was fitted to the dead leaf population from when the dead leaf population started increasing (Fig 4.8). The coefficient of x was taken to represent the rate of leaf death. There were variety differences. Variety NCo376 had the highest leaf death rate and ZN6 had the least. High leaf population varieties had higher leaf death rates than low leaf population varieties. The dead leaf population increased linearly with crop age. The straight-line equation could offer an option for modelling variety dead leaf numbers particularly if the triggers for start of leaf death can be identified. In this study it appears leaf death starts at peak total leaf population per hectare.

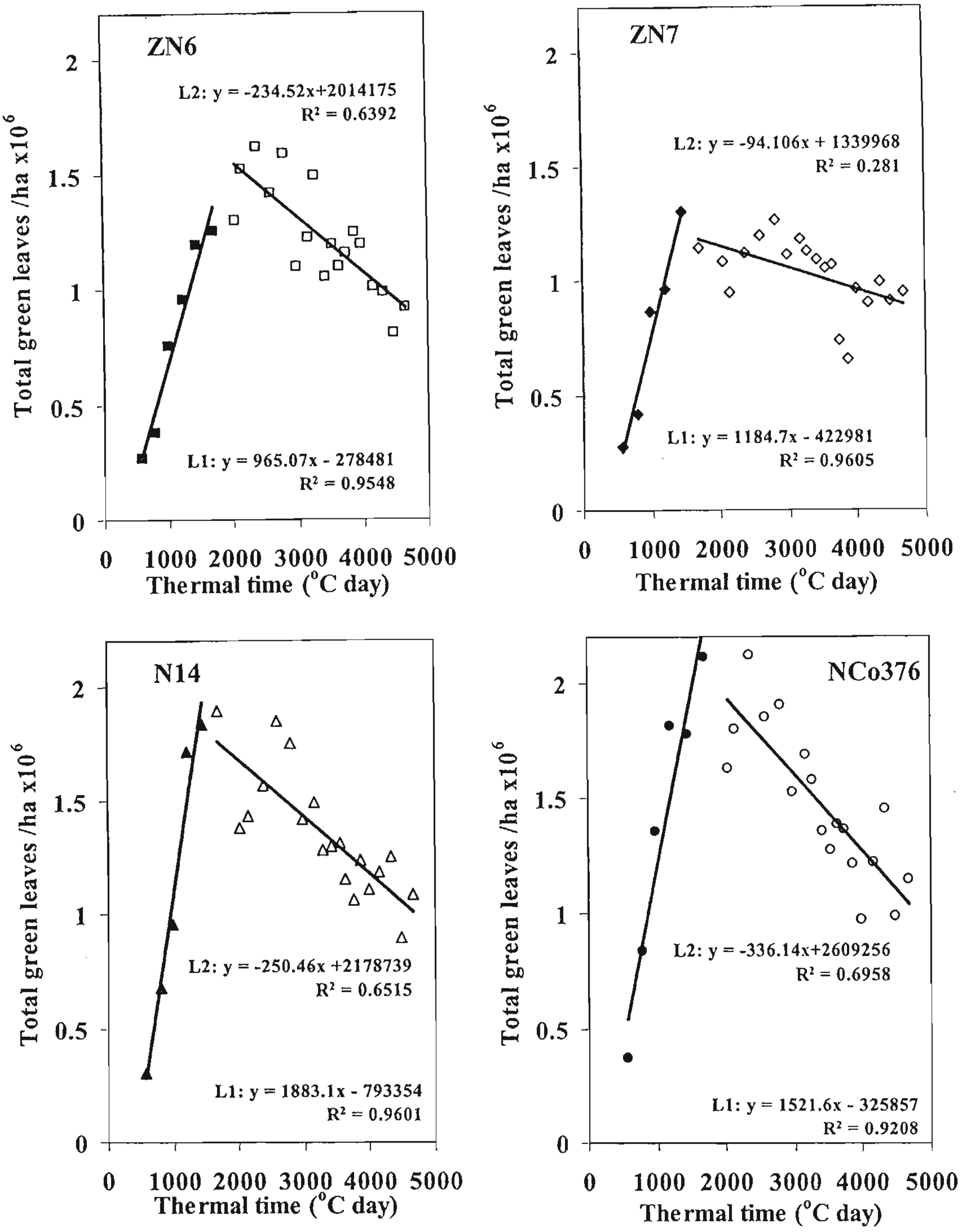


Fig. 4.5 The development of total green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 10°C. The fitted lines represent the broken stick model for the development of total green leaves per hectare. The lines L1 and L2 represent the first and second phases of development

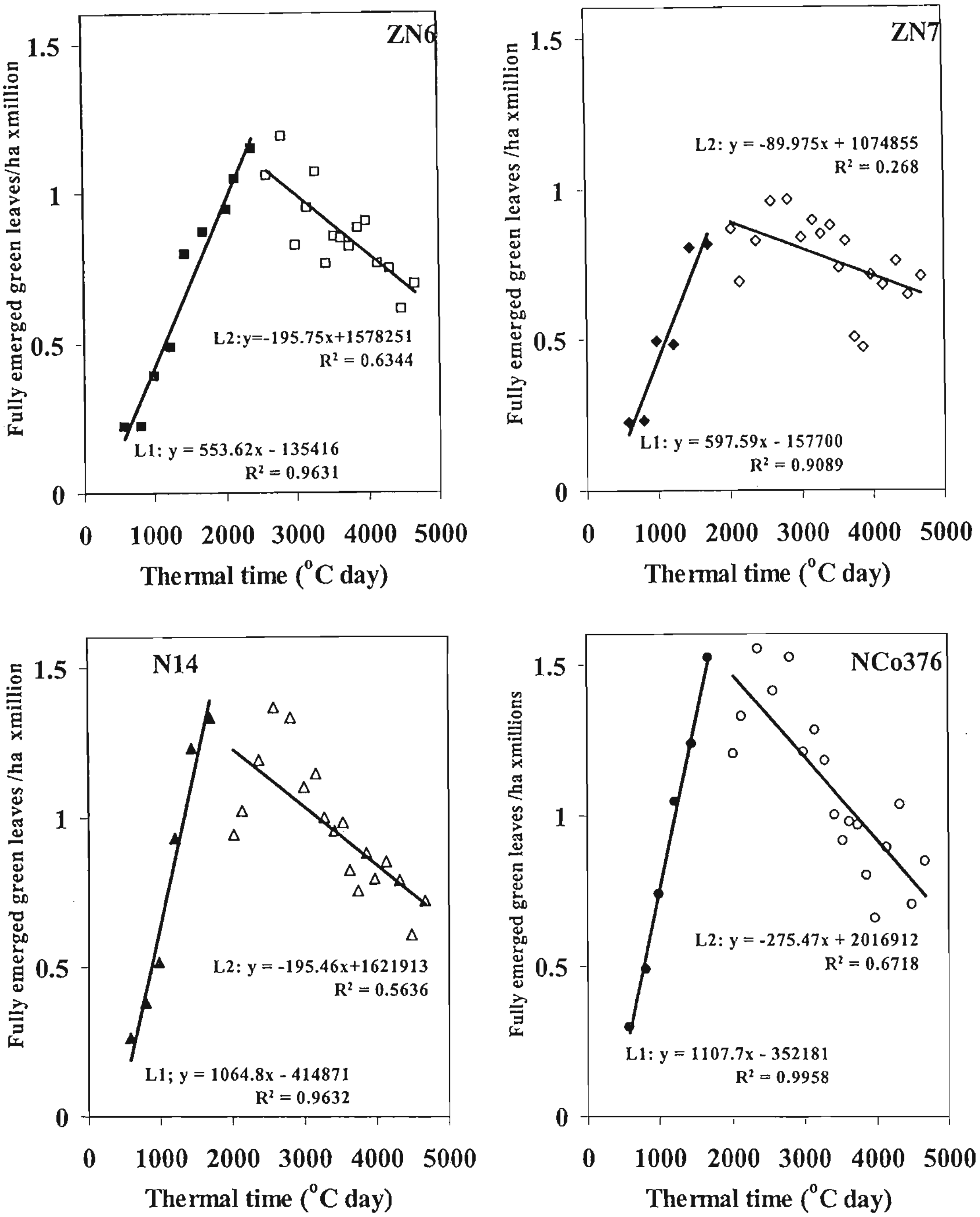


Fig. 4.6 The development of fully emerged green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 10 °C. The lines L1 and L2 represent the first and second phases of development

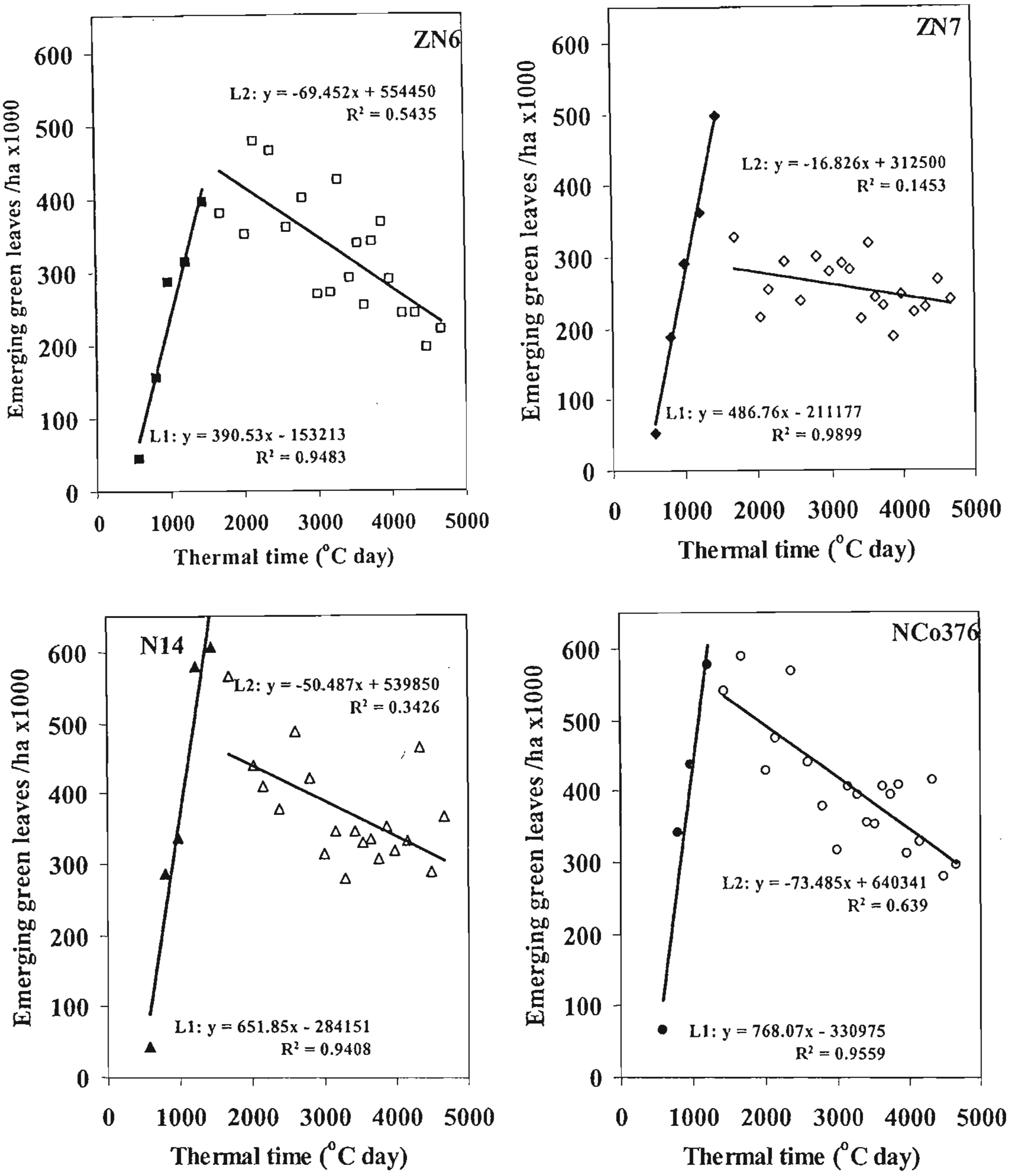


Fig. 4.7 The development of emerging green leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 10 °C. The lines L1 and L2 represent the first and second phases of development

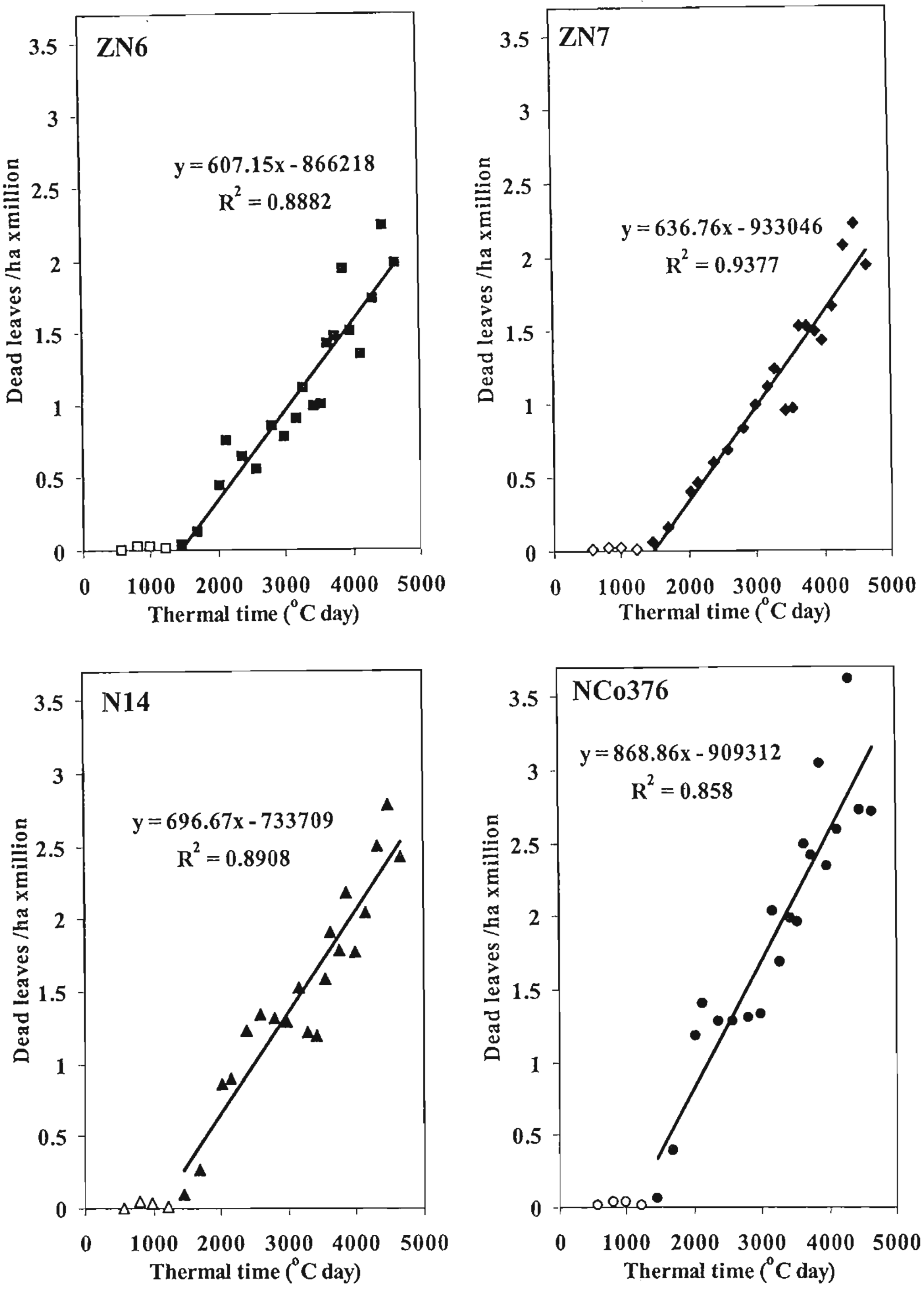


Fig. 4.8 The development of dead leaves per hectare of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 10 °C. The fitted line represents the period of accelerated leaf death

4.2.3 Green leaf numbers per stalk

There were differences in green leaf numbers per stalk between varieties throughout the crop cycle. The number of green leaves per stalk declined with crop age from above 12 to below 12 for all varieties (Fig. 4.9). Variety NCo376 had significantly fewer (P = 0,05) green leaves per stalk than the other varieties while variety ZN7 had significantly more (P = 0,05) green leaves per stalk than other varieties. The green leaves of all the varieties declined with age and variety NCo376 showed a steeper decline in green leaves per stalk compared to other varieties. A period of water stress was experienced when there was a labour action (104 to 124 days after planting). All the varieties had a decline in green leaves as a result, but the varieties recovered when normal irrigation resumed. Variety ZN7 started with a higher green leaf number per stalk than other varieties and towards the end of the crop cycle, its green leaf numbers per stalk was similar to that of N14. The decline in green leaf numbers with crop age appears to be varietal as all the varieties had different rates of decline. Varieties ZN6 and N14 had the least decline in green leaf numbers per stalk. The ability to maintain more green leaf numbers could increase PAR interception and probably result in higher yields.

4.3 Tiller growth and development

4.3.1 Tiller population development

Tiller population among varieties had three phases of development, tillering, tiller senescence and gradual decrease phase (Fig. 4.10). There was a rapid increase in tiller numbers during the tillering phase until the peak was reached and thereafter, there was a gradual decrease during the tiller senescence phase and the decrease continued during the gradual decrease phase. The timing of these phases varied among varieties. Varieties NCo376 and N14 followed a similar trend. Varieties N14 and NCo376 had tillering that reached the peak rapidly while ZN6 had reached its peak later. Varieties N14 and NCo376 had higher peak tiller population than both ZN6 and ZN7, and ZN7 had the lowest peak. Variety N14 had higher tiller senescence than NCo376 but these varieties reached the stable population at the same time. Variety ZN7 had the least tiller senescence and reached its stable population soon after the peak. The timing of stable population differed among these varieties. Variety ZN7 achieved stable population earlier. Varieties ZN6, N14 and NCo376 reached stable population at the same time.

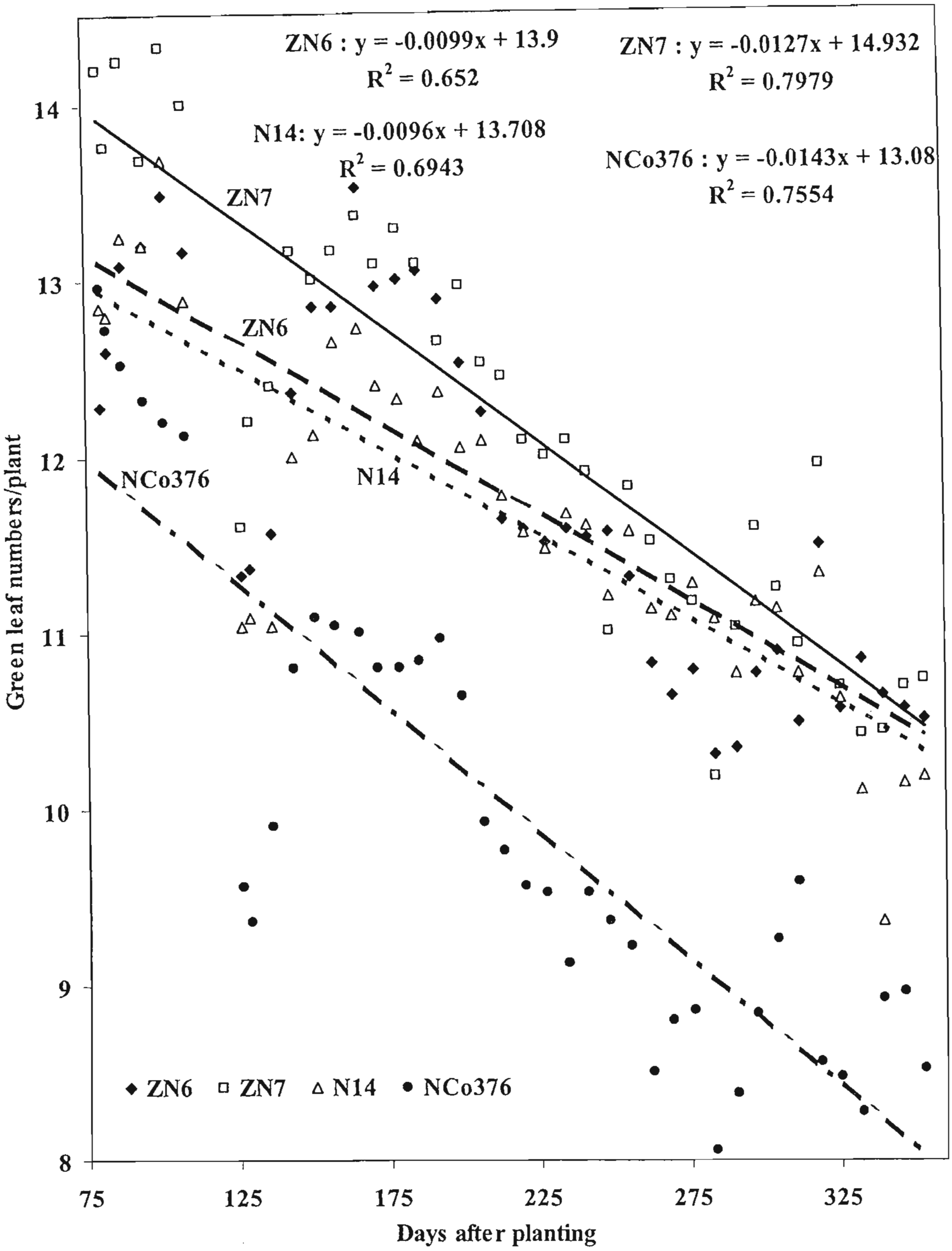


Fig. 4.9 The development of green leaf numbers per plant for varieties ZN6, ZN7, N14 and NCo376 plotted against days after planting. From day 100 to 125, irrigation was delayed by a strike.

Two straight lines were fitted to tiller population plotted against accumulated thermal time (Fig. 4.11). High R^2 values were obtained between the tillering phases and accumulated thermal time but except for N14, the senescence phase was less correlated to thermal time. The high R^2 in the tillering phase could mean that thermal time was the driver of the tillering process. The low R^2 in the senescence could mean that other factors such as PAR interception could be driving tiller senescence. When a regression analysis was done on the two phases, the data was highly significant (P = 0,01) for the two phases for all varieties suggesting that the tillering and tiller senescence phases were two-stage process and may not be adequately represented by polynomial equations as was suggested by Inman-Bamber (1994b). A broken stick model could describe these development phases better and the two lines break at the peak tiller population. The continued loss of large stalks could be serious constraint on yield.

Regression analysis was done for tiller population and thermal time calculated with different base temperatures to identify the tillering base temperature for the varieties (Table 4.1). The base temperature for NCo376 was 11 °C, which was lower than the 16 °C reported by Inman-Bamber (1994b). However, the other varieties had higher base temperatures than NCo376.

Table 4.1 The R^2 values (significant at P=0,01) of a polynomial fit between tiller population of four varieties and thermal time using different base temperatures (T_{base} in °C). The temperatures against the bold R^2 values represent the likely base temperatures for the varieties

Tbase	R^2 values			
(°C)	ZN6	ZN7	N14	NCo376
10	0,8059	0,7768	0,9386	0,6813
11	0,8060	0,7812	0,9394	**0,6815**
12	0,8063	0,7846	0,9403	0,6814
13	0,8068	**0,7860**	0,9412	0,6810
14	0,8077	0,7843	0,9423	0,6804
15	0,8088	0,7783	**0,9431**	0,6798
16	**0,8098**	0,7697	0,9431	0,6795
17	0,8096	0,7647	0,9419	0,6802

4.3.2 Tillering and tiller senescence rates

The proposed broken stick model (Fig. 4.11) was used to estimate the tillering and tiller senescence rates of varieties ZN6, ZN7, N14 and NCo376 versus accumulated thermal time calculated using a base temperature of 16 °C. The slope of the fitted trend lines represented the rates of tillering and tiller senescence. The R^2 values represented the correlation of tillering and tiller senescence to thermal time. Variety NCo376 had the greatest tillering rates and ZN7 had the least. Variety N14 had the greatest tiller senescence rates while ZN7 had the least. Low tiller population varieties (ZN6 and ZN7) had lower tillering and tiller senescence rates than high tiller population varieties (N14 and NCo376). The high tiller population varieties (N14 and NCo376) had higher R^2 values for both the tillering and tiller senescence phases compared to low tiller population varieties (ZN6 and ZN7). The high and low population varieties may be affected differently by factors affecting tillering and tiller senescence. Other varietal attributes may be contributing to the complexity of tillering and tiller senescence among varieties.

4.3.2.1 Length of tillering and tiller senescence

The length of tillering was determined as the period from emergence to peak tiller population while the tiller senescence was from peak to stable population (Table 4.2). The data showed that NCo376 completed tillering earlier than the other varieties. Variety N14 had the shortest tiller senescence phase while NCo376 had the longest. The rates of tillering and the length of tillering could potentially be used as variety parameters for modelling tiller development.

Table 4.2 Thermal time (°C.day) calculated with a base temperature of 16°C for varieties ZN6, ZN7, N14 and NCo376 during the tillering and tiller senescence phases

Variety	Tillering °C.day	Tiller senescence °C.day
ZN6	908,30	1637,05
ZN7	908,30	1637,05
N14	908,30	1171,05
NCo376	622,05	1923,30

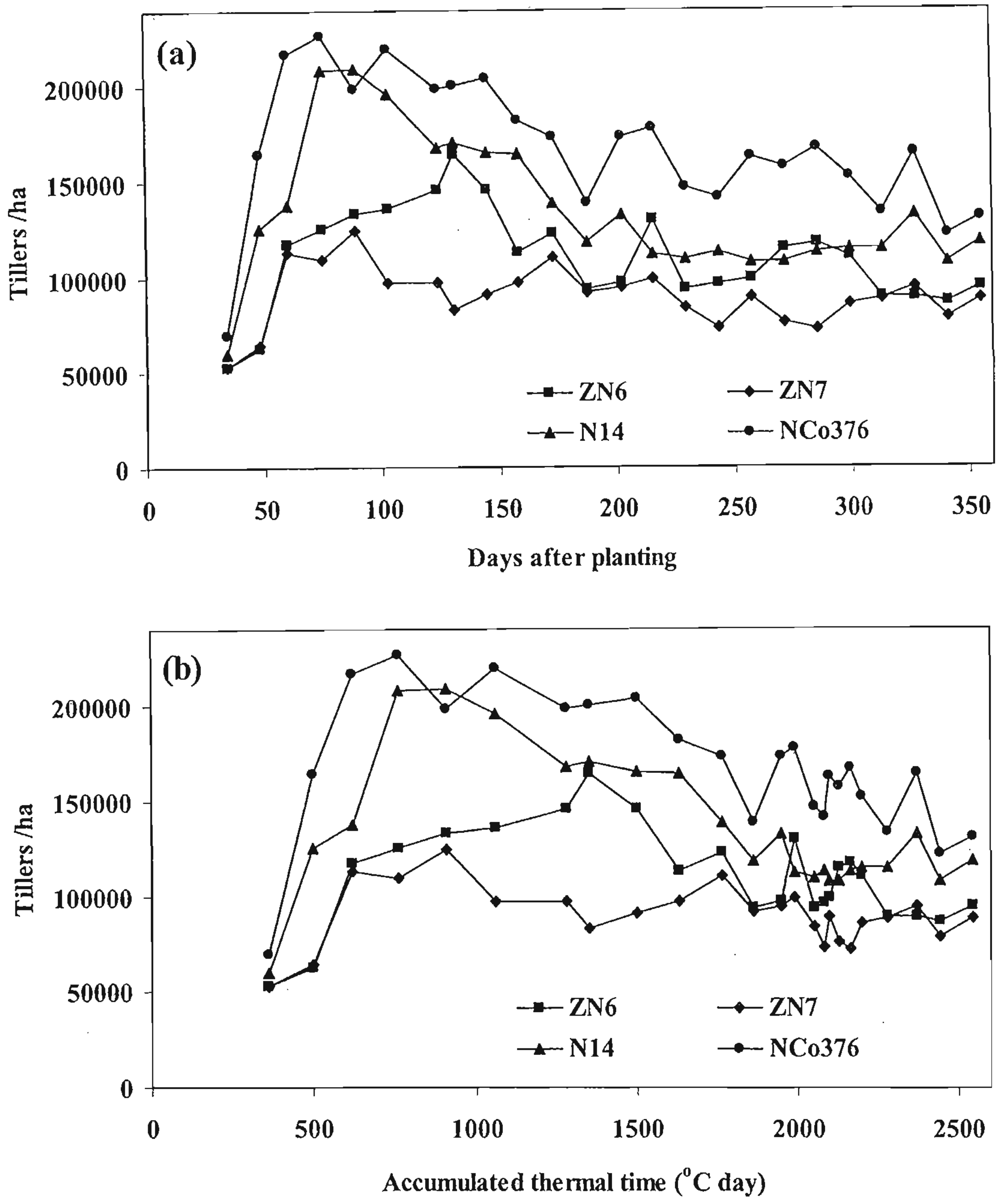


Fig. 4.10 The development of tiller population of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

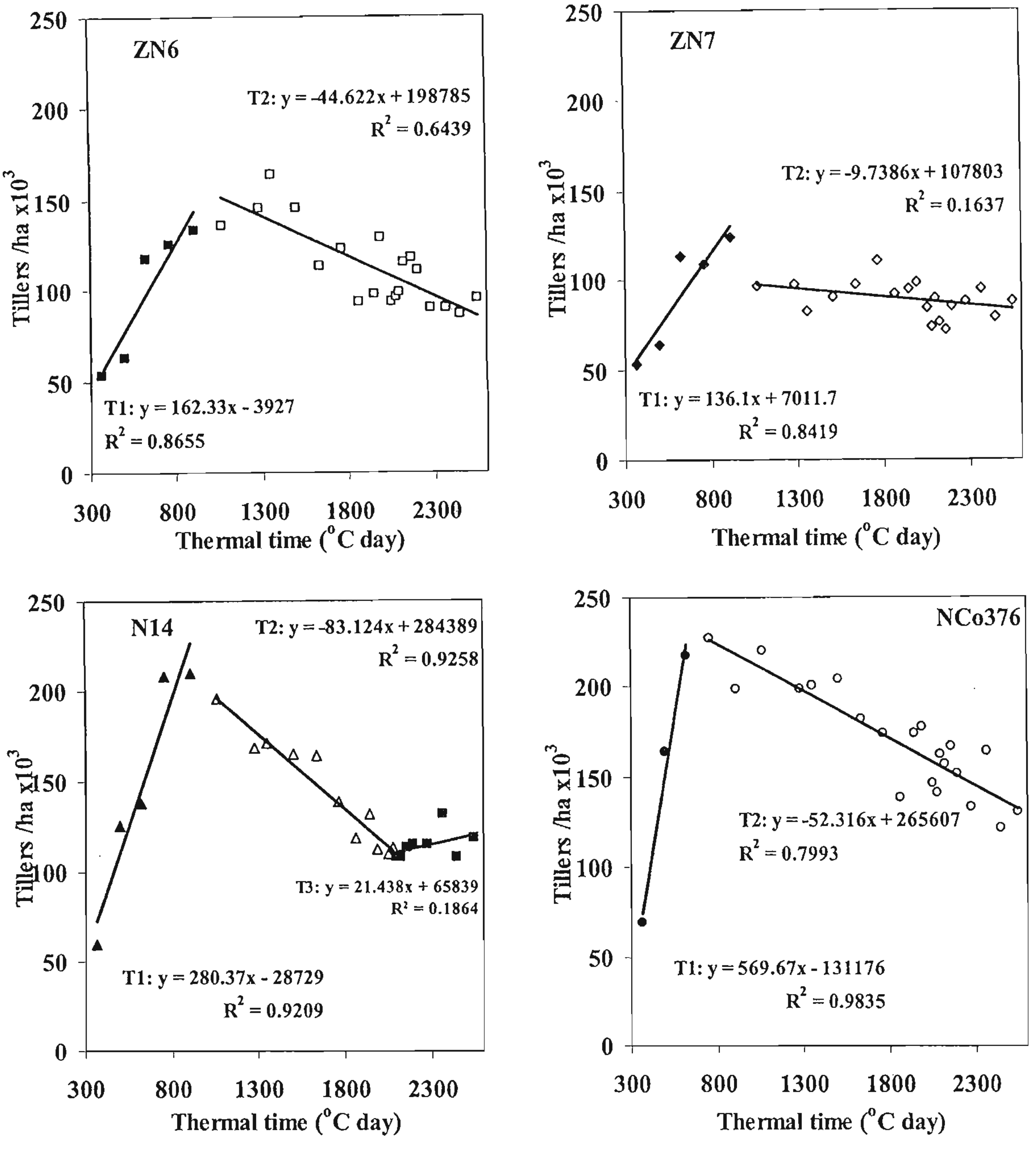


Fig. 4.11 The development of tiller population of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 16°C. The fitted lines represent the broken stick model for tiller population development. The lines T1, T2 and T3 represent the three phases of tiller development

4.3.3 Tiller heights

Tiller heights were a measure of canopy growth. When data for tiller heights were plotted against days after planting and accumulated thermal time (Fig. 4.12) the graph was sigmoid for all varieties. The graph was more sigmoid when plotted against days after planting than accumulated thermal time. The first phase of development was exponential or period of initiation of stalks, followed by a straight line or period of rapid stalk elongation and finally a slow growth during the sucrose accumulation phase. An exponential curve was fitted to the first phase and straight lines were fitted to the second and third phases of development (Fig. 4.13). The rate of growth was the coefficient of x. Varieties ZN7 and NCo376 had faster growth rates than ZN6 and N14 at the exponential phase. The exponential phase lasted the same time for all varieties. In the straight-line or stalk elongation phase, N14 had the fastest rate of stalk elongation while NCo376 had the least. Variety ZN6 had the longest stalk elongation period. The third phase was not visible in ZN6 and ZN7 had the fastest rate of growth in the third phase. Variety N14 had the shortest tillers during the stalk elongation phase while ZN7 had the tallest.

Goudriaan and Van Laar (1994) described three growth and development phases, an early exponential phase, a phase of full growth and a phase of ripening and senescence. During the exponential growth phase, most of the space around the plant2s was not occupied and each new leaf formed contributed to more PAR being intercepted so that growth increased even more. There was no mutual shading yet and the contribution of new leaves was identical to that of existing ones. The crop was still mostly vegetative in this exponential growth phase.

Later on, the leaves gradually started shading each other and this occurred above LAI of 3 or canopy closure. New leaf area contributed less to PAR interception and the linear growth phase started. The bulk of canopy formation occurred during this phase. The senescence phase started when PAR transmission to the bottom of canopy decreased below the threshold.

When tiller heights growth over time was regressed against thermal time it was found that the base temperatures were different among varieties. The base temperature that resulted from highest R^2 and the least standard error of the estimate when tiller heights were regressed against thermal time was the base temperature for the variety (Table 4.3). Variety N14 had the lowest base temperature while ZN7 and NCo376 had the highest.

Tiller senescence (Figs 4.10 and 4.11) occurred at the same time as the formation of internodes and the start of stalk elongation (Figs 4.12 and 4.13). As tillers died, rapid stalk elongation occurred. It appears that the same factors could be triggering the start of stalk elongation and tiller senescence.

Stalk or internode formation and stalk elongation started at the same time as peak leaf population. A threshold leaf number and leaf area per stalk may be required to initiate stalk elongation. The leaves are the source of photosynthates required to sustain internode formation and stalk elongation. Bezuidenhout (2000) noted that a threshold minimum leaf area may be required to sustain a tiller and any tillers with less than this threshold would die during the senescence phase. It could be possible that a minimum threshold of leaf area per tiller is required to initiate stalks and stalk elongation and may be those tillers that fail to achieve this threshold will eventually die before they initiate stalks. Varieties may also have different thresholds. More work is required to test this hypothesis.

The emergence of internodes and rapid stalk elongation phases were highly correlated to thermal time while the sucrose accumulation was not. The emergence of internodes and stalk elongation are therefore driven by thermal time.

Table 4.3 The R^2 values and standard errors (all significant at P=0,01) of a linear fit between tiller heights of four varieties and thermal time using different base temperatures (T_{base} in °C). The temperatures against the bold R^2 values and standard errors represent the base temperatures for the varieties

	R^2 values				Standard errors of estimate (cm)			
Tbase	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
11	0,9772	0,9751	0,9818	0,9781	14,214	15,330	12,722	14,096
12	0,9793	0,9779	**0,9821**	0,9811	13,520	14,429	**12,618**	13,092
13	0,9815	0,9809	0,9820	0,9843	12,801	13,435	12,654	11,957
14	0,9834	0,9838	0,9813	0,9874	12,116	12,377	12,929	10,703
15	0,9848	0,9863	0,9793	0,9902	11,610	11,365	13,585	9,429
16	**0,9849**	0,9879	0,9759	0,9920	**11,549**	10,706	14,661	8,502
17	0,9835	**0,9881**	0,9707	**0,9926**	12,065	**10,599**	16,176	**8,196**
18	0,9804	0,9868	0,9636	0,9916	13,163	11,144	18,020	8,739

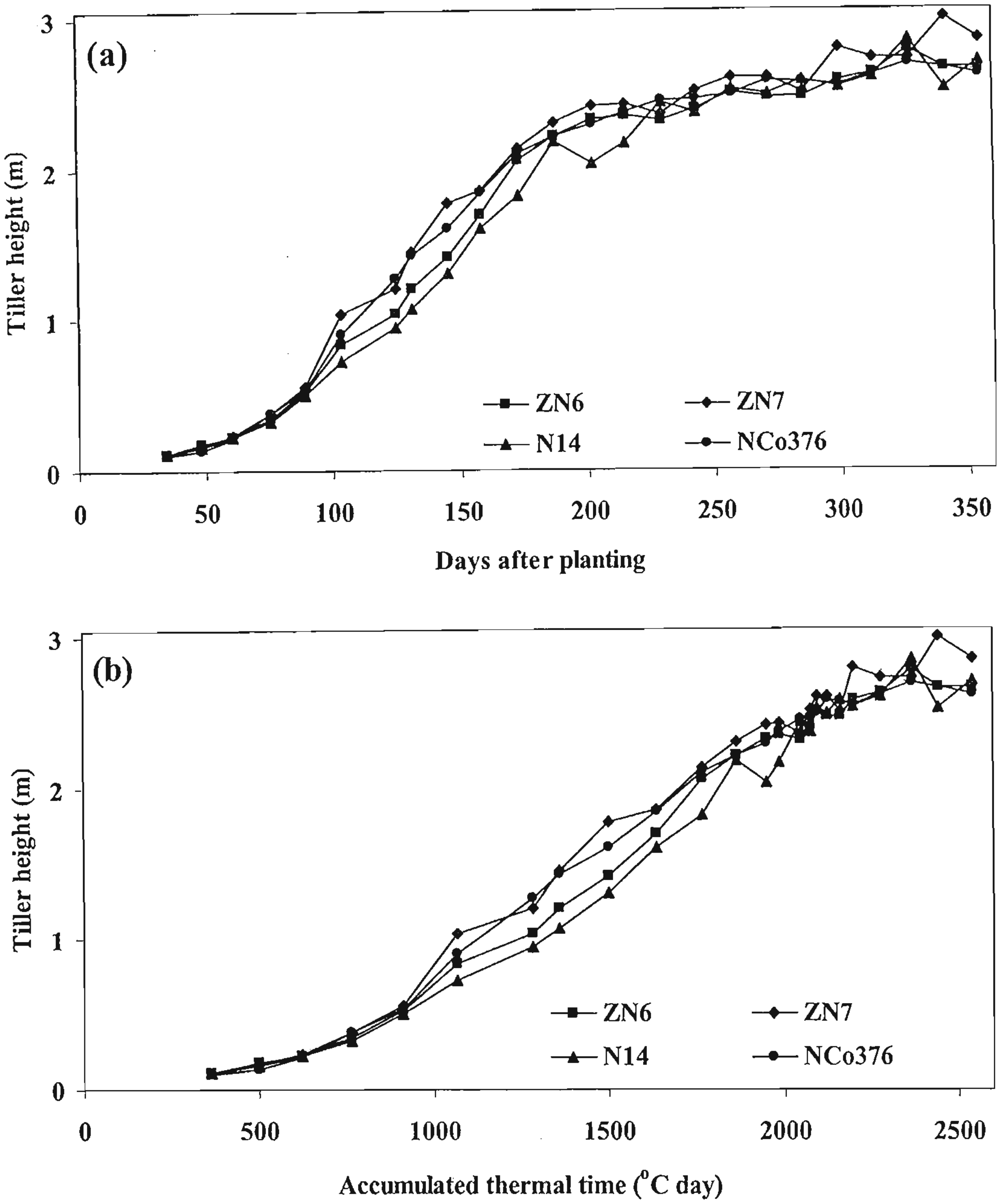


Fig. 4.12 The development of tiller heights of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

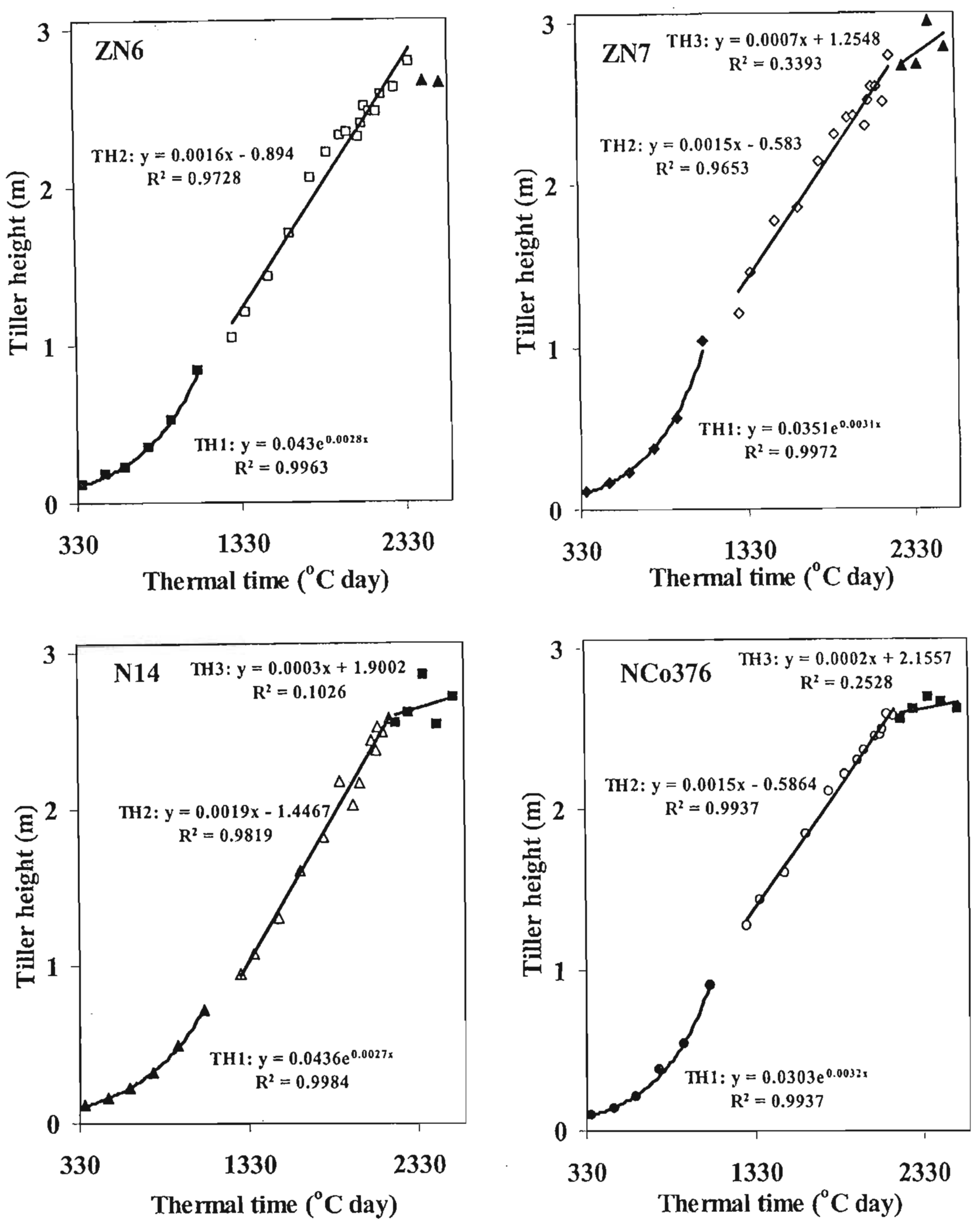


Fig. 4.13 The development of tiller heights of varieties ZN6, ZN7, N14 and NCo376 as a function of accumulated thermal time calculated using a base temperature of 16 °C. The fitted lines represent the broken stick model for tiller height development where TH1, TH2 and TH3 represent the three phases of tiller height growth and development

4.4 Canopy heights

Canopy heights were a measure of whole crop canopy growth. When data of canopy heights were plotted against days after planting and accumulated thermal time (Fig. 4.14), the development had a linear increase in the young crops and a decline phase at the end of the crop cycle. The decline in canopy heights at the end of the crop cycle coincided with crop lodging. It was also more difficult to measure canopy heights at this stage because of lodging. Variety ZN7 had the tallest canopy up to 36 weeks after planting and thereafter N14 had the tallest canopy. Variety N14 was more tolerant to lodging than the other varieties.

Canopy heights were regressed against accumulated thermal time to identify base temperatures for the varieties. The temperature that had the greatest R^2 and the least standard error of the estimate was the base temperature (Table 4.4). The base temperatures were higher than those determined for tillering and tiller heights (Tables 4.2 and 4.3). Variety ZN7 had the greatest base temperature and N14 had the least.

Table 4.4 The R^2 values and standard errors (significant at P=0,01) of a linear fit between canopy heights of four varieties and accumulated thermal time using different base temperatures (T_{base} in °C). The temperatures against the bold R^2 values and bold standard errors represent the base temperatures for the varieties

	R^2 values				Standard errors of estimate			
Tbase	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
16	0,9910	0,9734	0,9904	0,9842	11,257	21,264	12,619	14,948
17	0,9938	0,9794	**0,9915**	0,9879	9,298	18,731	**11,904**	13,049
18	**0,9951**	0,9838	0,9910	0,9902	**8,259**	16,587	12,268	11,770
19	0,9948	0,9866	0,9888	**0,9907**	8,532	15,097	13,637	**11,428**
20	0,9929	**0,9876**	0,9853	0,9898	9,978	**14,534**	15,652	12,011
21	0,9886	0,9866	0,9792	0,9867	12,631	15,124	18,612	13,724

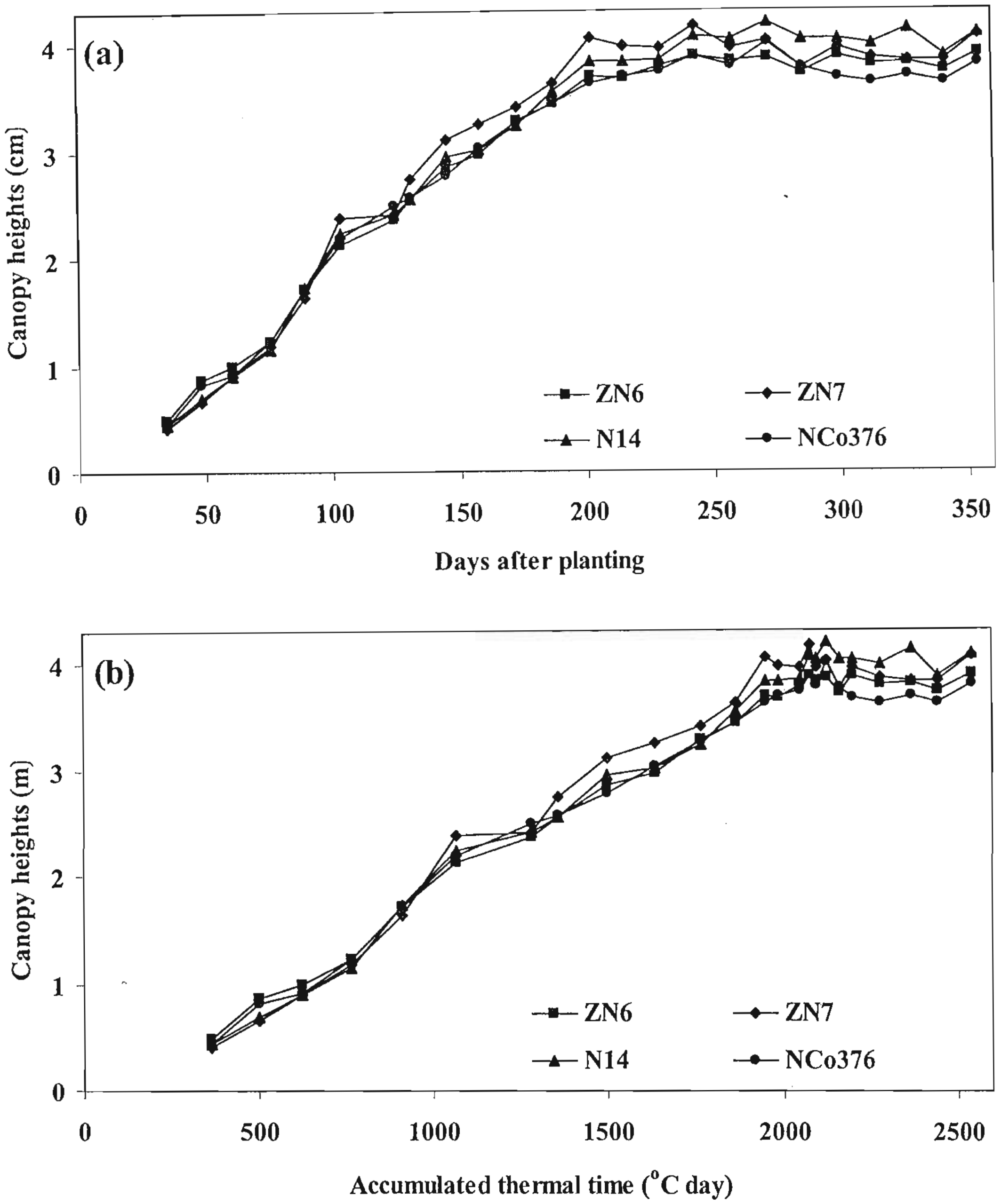


Fig. 4.14 The development of canopy heights of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

4.5 Stalk Development

4.5.1 Stalk population

Four phases of stalk population development were identified when stalks were plotted against days after planting and accumulated thermal time (Fig. 4.15), rapid stalk development, peak, decline and a stable stalk population. All the varieties except ZN7 showed all the four phases of development. The peak and stable phases were similar for ZN7. Varieties N14 and NCo376 maintained the longest peak population phase. The decline phase meant that some stalks died. There was no indication of stalk death in variety ZN7 and it appeared all the stalks formed matured to millable stalks. The varieties had different peaks and final stalk populations. Variety NCo376 had the highest peak and final stalk population while ZN7 had the least. The higher stalk population varieties (N14 and NCo376) reached their stable stalk population later than the lower stalk population varieties (ZN6 and ZN7).

4.5.2 Stalk height

When stalk height data was plotted against days after planting and accumulated thermal time (Fig. 4.16), the data showed a sigmoid growth pattern against days after planting and a straight line against accumulated thermal time. There were two phases of stalk elongation, rapid stalk elongation and stalk maturation. During the peak stalk elongation period, ZN7 had the tallest stalks while N14 had the shortest.

Stalk heights were regressed against thermal time calculated using different base temperatures. The temperature that had the highest R^2 and the least standard error of the estimate was the base temperature (Table 4.5). Varieties ZN6, ZN7 and NCo376 had base temperature of 16 °C while N14 had a base temperature of 11 °C.

4.5.3 Internode numbers per stalk

The formation of internodes showed a sigmoid pattern when plotted against days after planting and a straight line when plotted against accumulated thermal time (Fig. 4.17). Internode formation continued throughout the crop cycle. Variety ZN7 had the highest number of internodes and N14 had the least.

Internode numbers were regressed against accumulated thermal time calculated with varying base temperatures. The temperature that had the greatest R^2 and the least standard error of the estimate was the base temperature of the variety (Table 4.6). Variety N14 had the lowest base temperature and ZN7 and NCo376 had the highest. Internode formation occurred at lower temperatures (Table 4.6) than stalk elongation (Table 4.5).

Table 4.5 The R^2 values and standard errors (significant at P=0,01) of a linear fit between stalk heights of four varieties and accumulated thermal time using different base temperatures (T_{base} in °C). The temperatures against the bold R^2 values and standard errors represent the base temperatures for the varieties

	R^2 values				Standard errors of the estimate			
Tbase	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
10	0,9777	0,9686	0,9883	0,9779	10,936	12,944	7,801	10,701
11	0,9809	0,9723	**0,9887**	0,9811	10,124	12,155	**7,680**	9,881
12	0,9842	0,9763	0,9886	0,9845	9,202	11,252	7,693	8,942
13	0,9876	0,9804	0,9879	0,9880	8,171	10,230	7,934	7,880
14	0,9907	0,9845	0,9860	0,9912	7,081	9,110	8,536	6,734
15	0,9929	0,9880	0,9656	0,9937	6,154	8,014	9,656	5,709
16	**0,9934**	**0,9899**	0,9759	**0,9945**	**5,933**	**7,327**	11,208	**5,336**
17	0,9915	0,9897	0,9665	0,9930	6,774	7,421	13,196	6,023

Table 4.6 The R^2 values and standard errors (significant at P=0,01) of a linear fit between internode numbers of four varieties and accumulated thermal time using different base temperatures (T_{base} in °C). The temperatures against the bold R^2 values and standard errors represent the base temperatures for the varieties

	R^2 values				Standard errors of the estimate			
Tbase	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
2	0,9846	0,9739	0,9830	0,9769	0,6400	0,8659	0,6801	0,7679
3	0,9853	0,9748	**0,9830**	0,9777	0,6280	0,8516	**0,6800**	0,7547
4	0,9859	0,9757	0,9830	0,9785	0,6141	0,8363	0,6809	0,7407
5	0,9865	0,9766	0,9828	0,9793	0,6002	0,8201	0,6834	0,7260
6	0,9871	0,9776	0,9826	0,9802	0,5863	0,8031	0,6878	0,7106
7	0,9877	0,9785	0,9823	0,9811	0,5726	0,7854	0,6948	0,6949
8	0,9883	0,9795	0,9817	0,9819	0,5600	0,7674	0,7054	0,6791
9	0,9887	0,9805	0,9809	0,9827	0,5497	0,7496	0,7209	0,6641
10	**0,9889**	0,9813	0,9797	0,9834	**0,5435**	0,7332	0,7428	0,6510
11	0,9889	0,9820	0,9780	0,9838	0,5444	0,7202	0,7735	0,6419
12	0,9884	**0,9823**	0,9755	**0,9839**	0,5569	**0,7139**	0,8162	**0,6403**
13	0,9871	0,9820	0,9719	0,9833	0,5871	0,7197	0,8753	0,6517

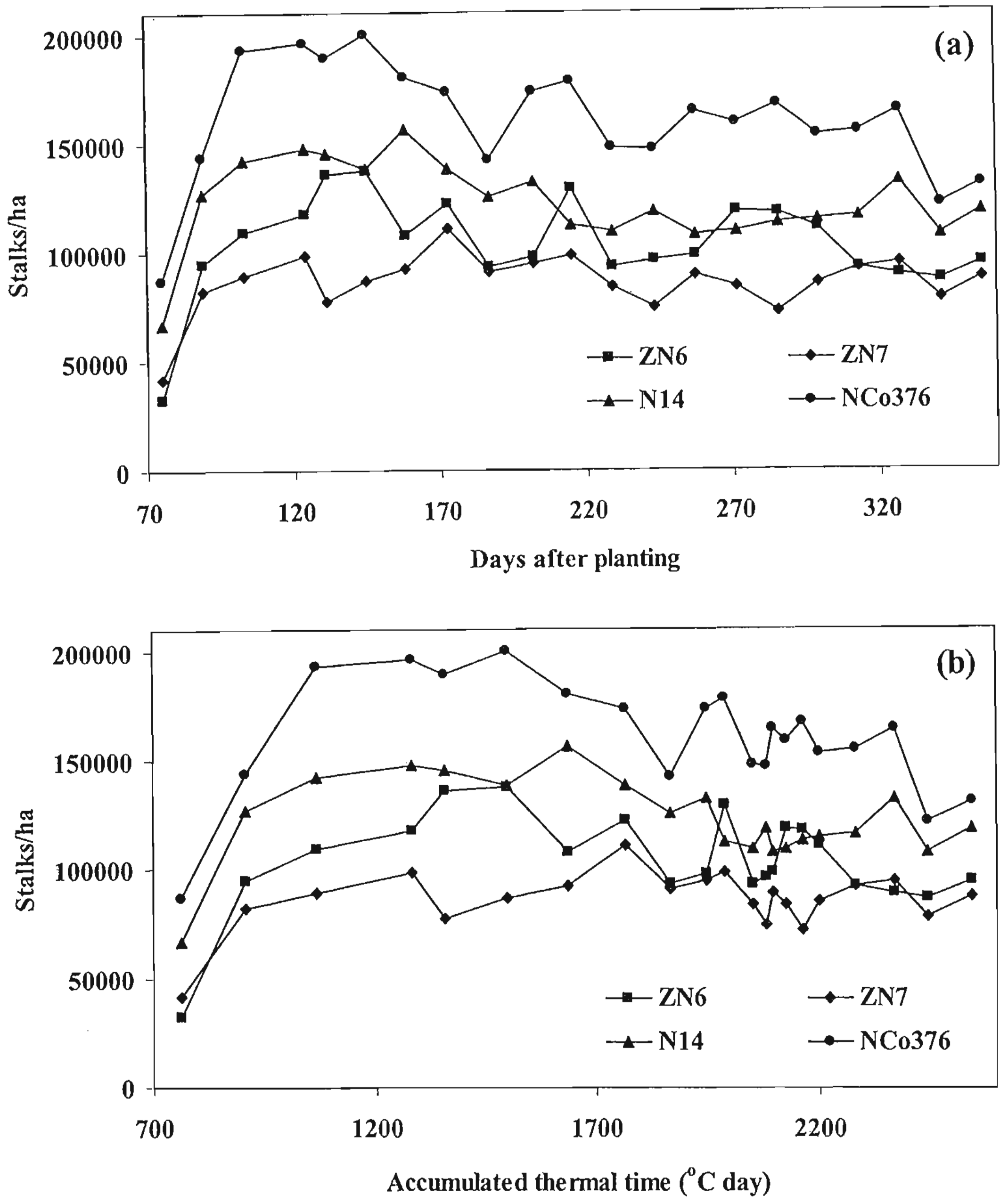


Fig. 4.15 The development of stalk population of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

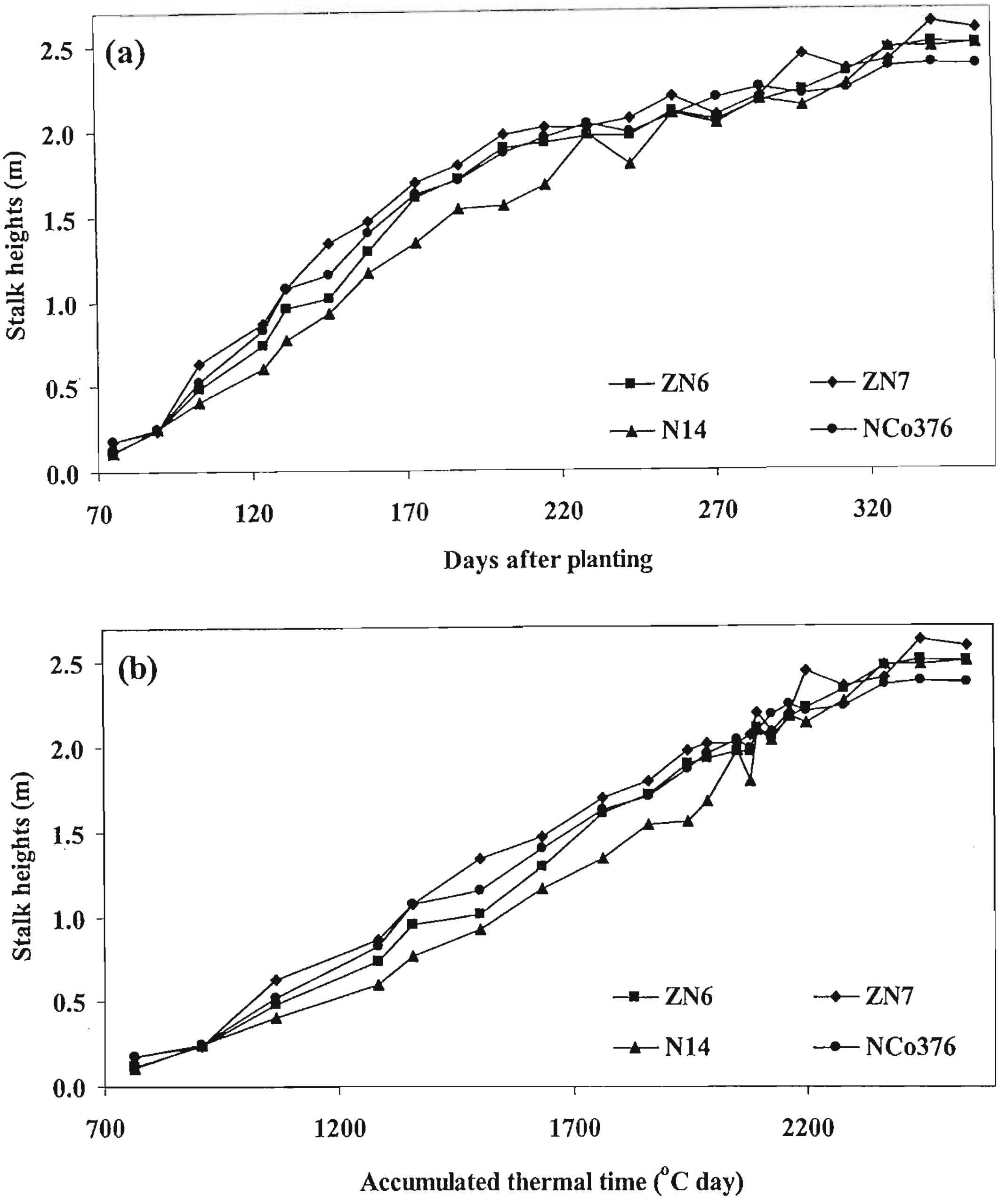


Fig. 4.16 The growth and development of stalk heights of varieties ZN6, ZN7 N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

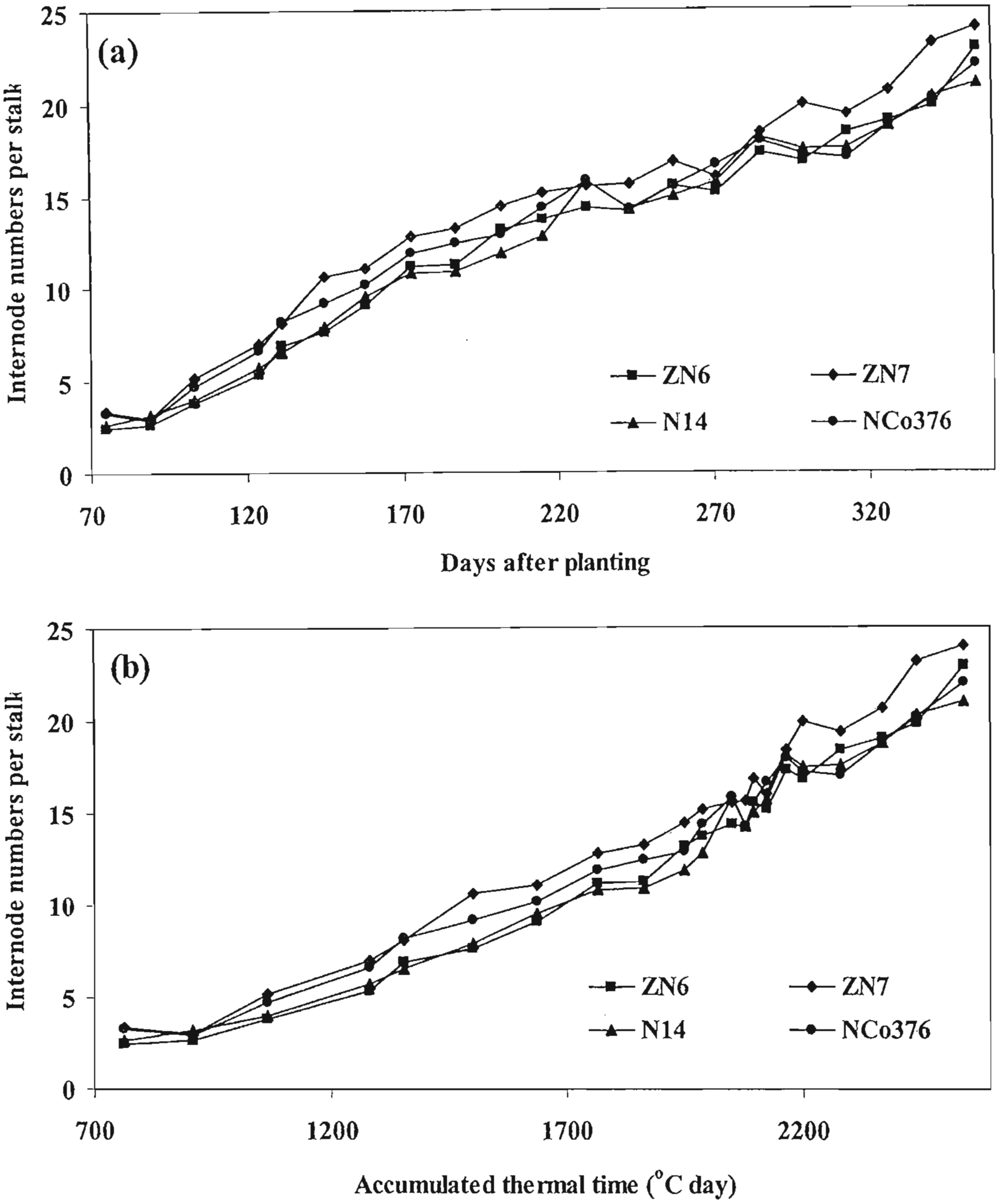


Fig. 4.17 The development of internode numbers per stalk of varieties ZN6, ZN7 N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated using a base temperature of 16 °C

4.6 Discussion

The phases of development of green leaf population and tiller population followed a similar pattern. High stalk population varieties (N14 and NCo376) had higher leaf and tiller population than low stalk population varieties (ZN6 and ZN7). The first phase was a rapid increase in population and a decrease in population after the peak. The varieties had different peaks, different rates of population increase and decrease for both leaf and tiller population. The varieties had different tillering and tiller senescence rates. Peak tiller population, peak leaf population and start of rapid stalk elongation appeared to coincide for each variety but these stages of development occurred at different times for different varieties. The data showed that tillering and leaf population increase was strongly correlated to air temperature while the senescence phases were less correlated. This may mean that the tillering and leaf population increase phases were driven by air temperature while the senescence phase could be driven by other factors such as intercepted PAR. Leaf death started after peak leaf population and thereafter increased linearly with crop age. Higher stalk population varieties (N14 and NCo376) had higher leaf death rates than low stalk population varieties. The varieties had different leaf death rates. Variety ZN7 had the highest number of green leaves per plant while NCo376 had the least. Variety NCo376 had the highest reduction in green leaf numbers per plant with crop age while varieties ZN6 and N14 had the least decline.

The tiller heights, stalk heights, canopy heights and internode numbers had three phases of development, exponential (initiation and emergence of internodes), linear (rapid stalk elongation) and linear (sucrose accumulation). Tiller senescence and rapid stalk elongation started at the same time. It could be possible that similar environmental and physiological factors initiate both tiller senescence and rapid stalk elongation. For example low PAR levels at the bottom of the canopy initiated tiller senescence (Inman-Bamber, 1994b). Inman-Bamber (1994b) reported that NCo376 initiated tiller senescence when the canopy intercepted 70% of PAR. This could possibly be the amount of PAR interception required to generate photosynthates for initiation of stalks elongation. Bezuidenhout (2000) noted that there could be a minimum leaf area per tiller and tillers with less than that leaf area are likely to die. The leaves with the maximum leaf area of a variety are likely to be developed by peak leaf population thus providing the threshold leaf area for initiation of stalk elongation and also shading out smaller tillers with leaf area below the threshold which eventually die.

The base temperatures for initiation and emergence of internodes was lower than for tillering, tiller heights, canopy heights and stalk heights. This may mean that initiation of internodes was less sensitive to low air temperatures and internodes were likely to be formed even when stalk elongation had stopped due to low temperatures. Tillering and stalk elongation of ZN6 would occur at 16 °C. Tillering of ZN7 and NCo376 occurred at lower base temperatures than that of ZN6 and N14. Stalk elongation of varieties ZN6, ZN7 and NCo376 required a base temperature around 16 °C while that of N14 could be between 11 and 12 °C (Table 4.7). This indicates that internode formation was less sensitive to low temperatures and are likely to be formed under lower air temperatures. However, these internodes will not elongate fully resulting in short internodes. The canopy heights required higher base temperatures to grow. This could be the reason why visually cane crop canopies changes very little in height during winter and increases rapidly in summer. The other reason could be that the internodes formed in winter do not elongate fast and therefore the stalk heights increases slowly and thus resulting in a slow increase in canopy heights of the whole crop. The crop canopy of N14 is likely to increase more than the other varieties. Variety N14 is therefore likely to grow better in winter than the other varieties because of its lower base temperatures for stalk elongation and internode formation.

The above variety differences can be used to develop parameters for modelling variety differences in canopy development.

Table 4.7 The base temperatures (°C) for tillering, tiller heights, stalk heights, internode initiation and canopy heights of varieties ZN6, ZN7, N14 and NCo376

	ZN6	ZN7	N14	NCo376
Tillering	16	13	15	11
Tiller heights	16	17	12	17
Stalk heights	16	16	11	16
Internode formation	10	12	3	12
Canopy heights	18	20	17	19

Chapter 5 PHYSIOLOGICAL PARAMETERS FOR MODELLING SUGARCANE VARIETY DIFFERENCES IN CANOPY DEVELOPMENT[1]

5.1 Introduction

The ability of simulation models to predict growth and development as affected by soil and weather conditions, agronomic practices and cultivar traits may make such models attractive tools for crop improvement (White, 1998). Models have been used to examine the effects on yield of specific traits or suites of traits representing possible crop ideotypes. White (1998) argued that models were highly suitable for aiding breeders in understanding genotype by environment interaction, particularly when linked to geographical information systems. As crop models become more mechanistic and comprehensive, they can be used to mimic genetic characteristics of plants. Crop models were used to hypothesize genetic traits for optimizing crop performance in specific environments (Boote *et al.*, 1996). Simulation models have been used for this purpose in soy beans (*Glycine max L*), groundnuts (*Arachis hypogea L*) and cotton (*Gossypium hirsutum L*).

Crop growth models have excellent potential for evaluating genetic improvements, for analyzing past genetic improvements from experimental data and for proposing plant ideotypes for target environments. Crop models used for these plant-breeding applications should be sufficiently mechanistic that processes can be investigated in a manner familiar to crop physiologists and plant breeders. The crop models must consider a sufficient number of cultivar specific traits descriptive of life cycles, phases, vegetative traits and reproductive growth attributes. More physiological insight into primary processes such as source-sink relationships and morphological development will be needed for enhanced application of the models in breeding programmes (Boote *et al.*, 2001).

Crop models are increasingly used to support agronomic management practices. Examples for sugarcane include irrigation planning and scheduling (McGlinchey, 1996 a, b), drying off and crop cycle management (Inman-Bamber, 1991b and 1994a). The potential also exists to assist in variety choice to maximize sucrose production (Zhou, 2001). However, at present models lack the ability to simulate differential responses of varieties to the environment. Research is required to address this shortcoming.

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[1] This chapter is based on a paper presented by Zhou *et al.* (2002) at the South African Sugar Industry Agronomists Association Workshop held on 22 October 2002 at SASA, Kwa-Shukela Board Rooms, Flanders Drive, Mount Edgecombe. Theme: Varieties.

This chapter attempts to quantify varietal control of canopy development by defining key physiological parameters and determining the values for these for selected varieties grown in Zimbabwe. The basic requirements for variety parameters to be useful for simulating variety response to the environment are that:

1. the value should be stable across environmental conditions,
2. that significant differences in the value exists between varieties, and
3. it should also have some physiological meaning.

Aspects of canopy development that will be treated in this chapter are thermal time for leaf and shoot appearance, leaf area, tiller appearance, tiller senescence and canopy architecture. The influence of these parameters on formation of the crop canopy and interception of PAR will also be investigated for varieties ZN6, ZN7, N14 and NCo376.

The objective of this chapter is to determine physiological parameters that can be used in modelling variety differences in canopy development. These are the parameters that would be used to differentiate between varieties and can therefore possibly be used as genotype coefficients.

5.1.1 Parameter descriptions

Temperature drives many of the processes responsible for phenological development in a crop. The effect of temperature is often quantified using the concept of thermal time with air temperature being the most convenient measure of temperature. Thermal time is defined as the cumulative value of the mean daily temperature minus the base temperature. Base temperature is defined as the temperature below which the rate of development is zero.

Development of leaf canopy will be determined by the rate of appearance of new leaves, the final size of leaves and the number of tillers carrying leaves. Parameters are therefore needed to quantify these.

PAR transmission within the canopy controls the onset of tiller senescence. This will be influenced by canopy architecture, which could be quantified by the canopy extinction coefficient. It is assumed that PAR is transmitted through a crop canopy according to Beer's Law ($PAR_{intercepted}/PAR_{incident} = 1-e^{-k.LAI}$) where LAI is the leaf area index and k is the extinction coefficient (Monteith, 1973; Monteith and Unsworth, 1990). The parameters that were calculated from field experiment measurements are shown in Table 5.1.

Table 5.1 A description of variety parameters

Parameter name	Parameter description	Units
TTE	Thermal time requirement for shoot emergence. The thermal time from planting or ratooning to the emergence of 50% of potential shoots	°C day
TTL	Thermal time requirement for the appearance of a leaf, called a phyllochron. The thermal time between the appearance of successive leaves	°C day
TTTP	Thermal time requirement to reach peak tiller population	°C day
TTSE	Thermal time requirement to start of stalk elongation	°C day
LAMAX	Surface area of the youngest biggest leaf of unstressed crop	cm^2
LNO	Leaf number of the youngest biggest leaf	Number
LTT	PAR transmission threshold for start of tiller senescence	Fraction
K	PAR extinction coefficient for a canopy	
TPOPMAX	Peak tiller population is the maximum number of tillers reached during the life cycle of an unstressed sugarcane crop	Number
TPOPF	Mature tiller population is the number of tillers remaining when 1600 °C day of thermal time has accumulated since ratooning or planting	Number

The leaf appearance is defined by the phyllochron intervals. Phyllochron 1 (P1) is the rate of leaf appearance (°C.day) for leaves 1 to 14 and phyllochron 2 (P2) is the rate of leaf appearance for the 14th leaf upwards on a tiller. The phyllochron switch is the leaf number when leaf appearance decreases and changes from P1 to P2 (Fig. 5.2).

5.2Thermal time requirements

5.2.1 Shoot appearance

In experiment 3, the number of emerged cane shoots was recorded up to 37 days after planting while for experiment 4 the numbers of emerged eyes were recorded up to 68 days after planting (Table 5.2). Variety N14 had the lowest thermal time to 50% emergence in both experiments while variety ZN6 had the highest thermal time (TT10 and TT16) to 50% emergence in both experiments. At termination of the germination counts, ZN6 and ZN7 had lower percentage of emerged eyes compared to N14 and NCo376 (Table 5.2). The trend for soil temperature was the same as that for air temperature. The data on days to 50% emergence and the thermal time to 50% emergence showed no significant differences among varieties at the 95% level of statistical significance. The difference in TTE between the two experiments was the least when using a base temperature of 16 °C. This suggested that 16 °C was a more likely base temperature than 10 °C. There were significant differences (P = 0,01) among emerged eyes recorded at 68 days after planting in experiment 4. The difference between the total numbers of emerged tillers at the termination of counting was varietal. It appeared that higher stalk population varieties had a higher germination percentage than lower stalk population varieties. The cumulative soil temperature to 40% emergence had a lower coefficient of variation and therefore could be a more reliable driver of emergence than air temperature but it is more difficult to measure due to the distance between the weather station equipment and the site.

5.2.2 Leaf appearance

5.2.2.1 Broken stick model

The phyllochron 1, phyllochron 2 and the phyllochron switch of the varieties was determined using accumulated thermal time calculated using a base temperature of 10 °C. This value was determined by Inman-Bamber (1994b). Inman-Bamber (1994b) analysed data from NCo376 and N12 and concluded that their base temperatures were similar. Inman-Bamber (1994b) also concluded that the variation in base temperatures for leaf appearance in South African sugarcane varieties was likely to be small. Hammer *et al.* (1993), using a similar regression procedure used by Inman-Bamber (1994b) found a comparatively small range in base temperature (10,5 to 12,2) for leaf appearance in grain sorghum hybrids. Therefore a base temperature of 10 °C was used and assumed to vary little between varieties used in this study.

Table 5.2 The number of eyes planted per plot, thermal time to 50 % emergence of planted eyes using TT10 and TT16 of varieties ZN6, ZN7, N14 and NCo376 and the percentage of emerged eyes at 68 and 37 days after planting of varieties ZN6, ZN7, N14 and NCo376 in experiment 3 and 4. The plot size was 25 m^2 for experiment 3 and 255 m^2 for experiment 4

Variety	Number of eyes planted per m^2		Thermal time (°C.day) to 50% emergence at TT10		Thermal time (°C.day) to 50% emergence at TT16		Cumulative soil Temperature (°C.day) to 40% emergence	% emergence 68 and 37 days after planting	
	E4	E3	E4	E3	E4	E3	E4	E4	E3
ZN6	10,3	10,1	654,1	378,7	262,4	228,7	418,50	53,7	67,9
ZN7	10,4	10,2	566,8	351,0	219,1	213,0	401,60	57,2	64,1
N14	9,6	9,4	531,3	317,2	199,6	191,2	355,70	60,9	80,1
Nco376	9,8	9,6	586,2	378,7	228,4	228,7	384,87	65,4	85,9
Significance	0,000	-	0,130	-	0,142	-	0,076	0,013	-
S.E. mean	0,05	-	30,83	-	16,11	-	13,72	1,73	-
C.V. (%)	0,84	-	9,13	-	12,27	-	6,09	5,06	-

To calculate phyllochron 1 and 2, the phyllochron switch was identified first. A regression analysis of accumulated thermal time (independent variable) against leaf number (dependent variable) was applied at various leaf numbers from leaf 5 to leaf 25 as the phyllochron switch (Fig. 5.1). The R^2 values calculated from this analysis for phyllochron 1 and phyllochron 2 at different leaf numbers as the switch point was plotted against leaf number. The point where the line graphs for phyllochron 1 and phyllochron 2 intersected was the phyllochron switch for the variety (Table 5.3). The switch for varieties ZN7 and NCo376 occurred before the intersection. The phyllochron switch for variety NCo376 was higher than was found by Inman-Bamber (1994b). Higher phyllochron switches were found particularly for varieties ZN6 and ZN7.

Using the phyllochron switches, the data on leaf emergence was plotted against accumulated thermal time calculated using a base temperature of 10 °C. The graphs represented the broken stick with the phyllochron switch as the breakpoint. Lines and equations were fitted to the data (Fig. 5.2). The equations for the best-fit lines were used to calculate phyllochron 1 and 2 for each variety. Phyllochron 1 and 2 were calculated for varieties ZN6, ZN7, N14 and NCo376 by solving the equations for phyllochron 1 and 2 respectively (Table 5.4). The broken stick was used as it represents the equations used in the CANEGRO model.

Variety ZN7 had the fastest rate of leaf emergence and produced the highest number of leaves per tiller (Tables A2.1 and A2.2). Variety N14 had the least phyllochron 1 interval. NCo376 had the highest value of phyllochron 2 intervals. Inman-Bamber (1994b) reported higher values for phyllochron 1 (109) and lower for phyllochron 2 (169) in a study of a ratoon crop of NCo376 compared to values found in this study. The data also showed that there were variety differences for leaf emergence for both phyllochron 1 and phyllochron 2 intervals. Leaf emergence was not constant throughout each portion of the broken stick (Figs 5.2 and 5.3).

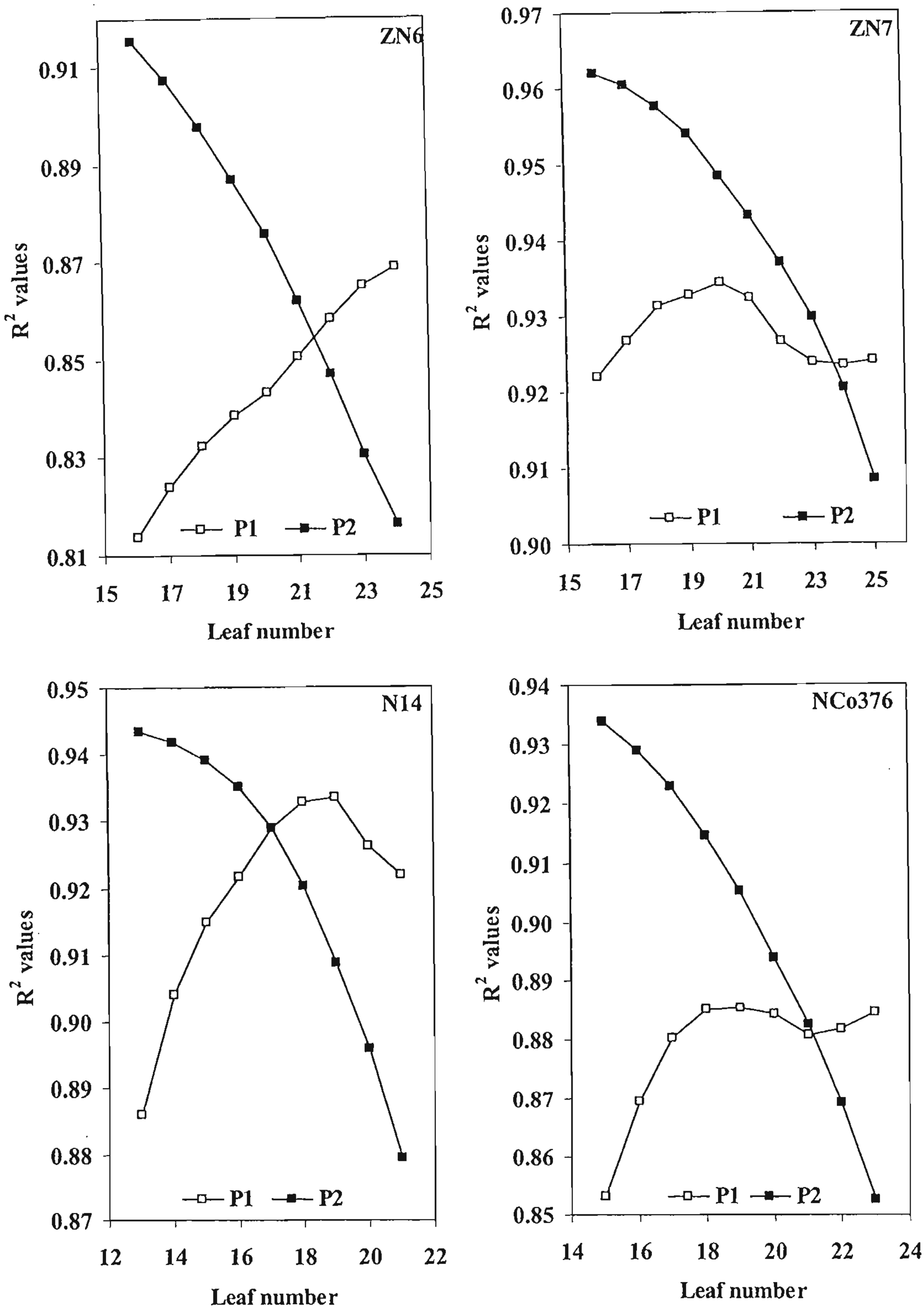

Fig 5.1 The relationship between the R^2 values of phyllochron intervals 1 and 2 calculated with different leaf numbers as the phyllochron switch for varieties ZN6, ZN7, N14 and NCo376

Table 5.3 The leaf numbers where varieties ZN6, ZN7, N14 and NCo376 leaf emergence change from phyllochron 1 to phyllochron 2. This leaf number is the phyllochron switch

Variety	Phyllochron switch (leaf number)
ZN6	21
ZN7	20
N14	17
NCo376	18

5.2.2.2 Gradual increase of phyllochron intervals

Results suggested that the conventional "broken stick approach" (Inman-Bamber, 1994b) would not adequately explain leaf emergence because the leaf emergence rate was not constant throughout the two portions of the broken stick (Figs 5.2 and 5.3). The use of gradual increase from early to later leaves provides a better estimation of thermal time requirements for leaf emergence. It is therefore suggested that the phyllochron for leaves 1 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 25 to 30, 30 to 35, 35 to 40 (TTL5 to TTL40), are considered as variety parameters (Tables 5.3 and 5.4). The phyllochron intervals increased up to a peak and then decreased at the end of the crop cycle. Variety ZN7 produced the highest number of leaves and NCo376 produced the least number. Variety ZN7 had the least phyllochron intervals up to leaf number 30 and that explained its high leaf number.

Table 5.4 Phyllochron intervals (P1 and P2) for two growth stages of sugarcane varieties ZN6, ZN7, N14 and NCo376 using base temperature of 10 °C

Variety	Phyllochron 1 (°C.day)	Phyllochron 2 (°C.day)
ZN6	99,01	185,19
ZN7	70,92	172,41
N14	68,03	188,68
NCo376	77,52	200,00

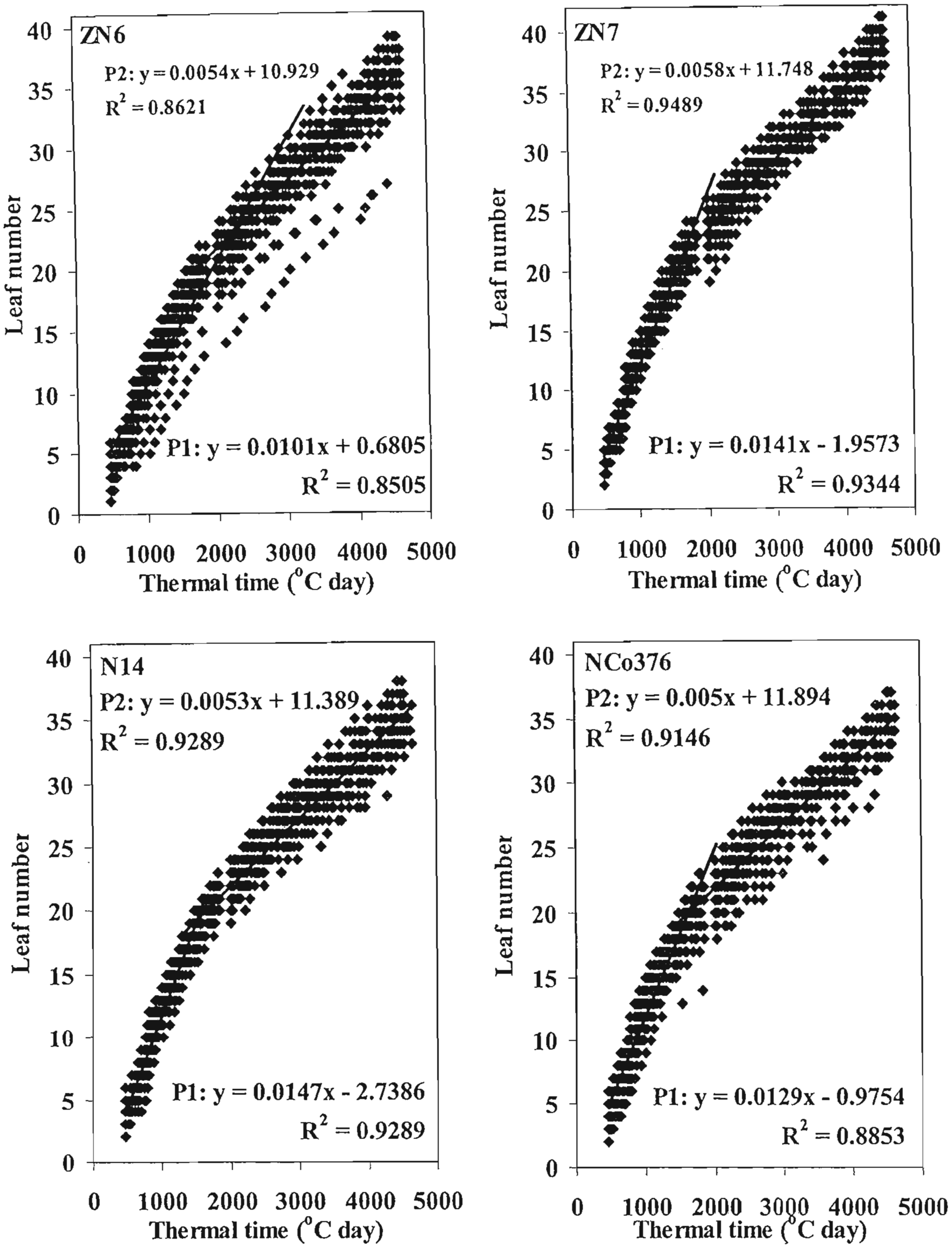

Fig. 5.2 Total leaf number per stalk in relation to thermal time with base temperature of 10 °C for varieties ZN6, ZN7, N14 and NCo376

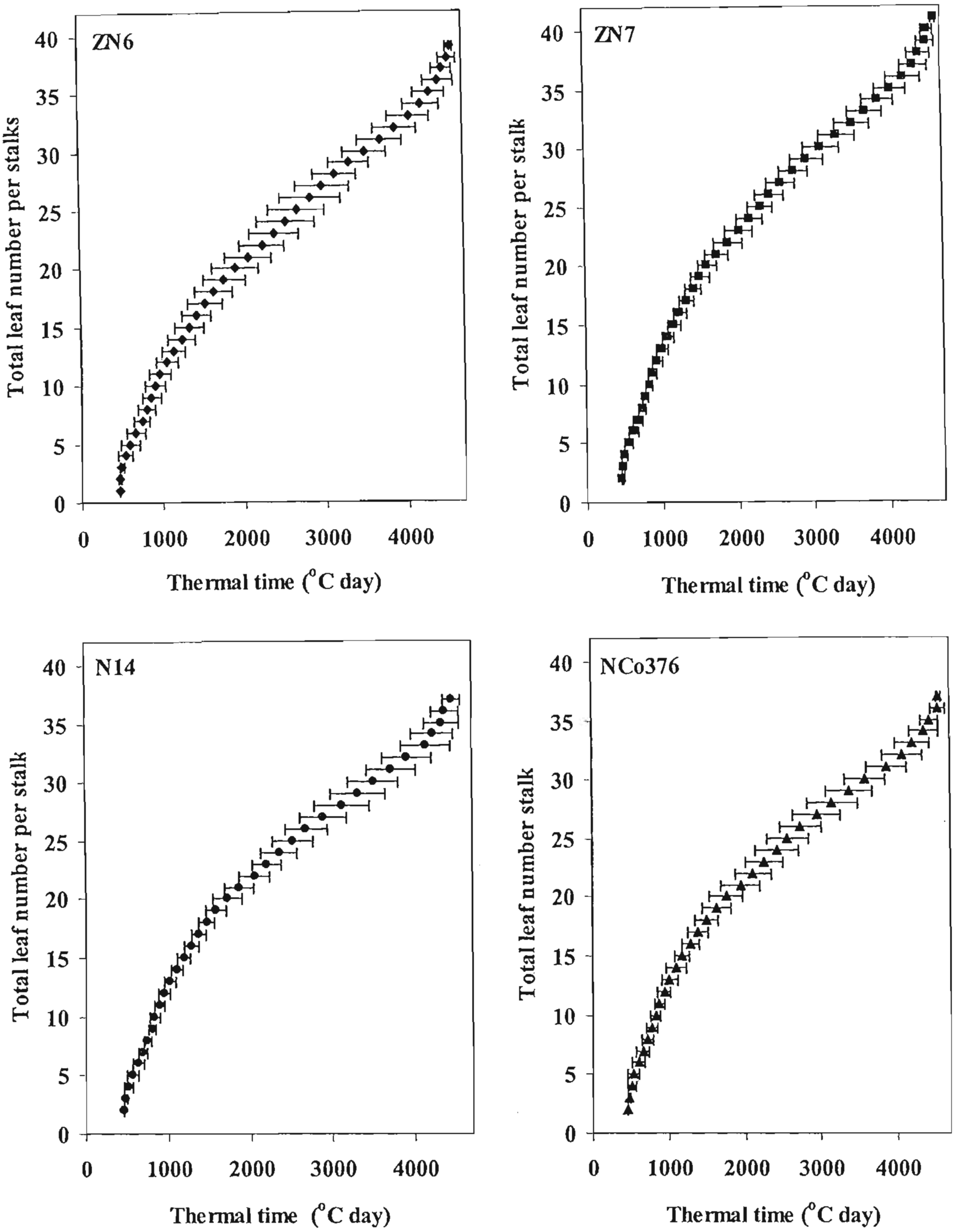

Fig. 5.3 The total number of leaves per stalk in relation to average accumulated thermal time calculated with a base temperature of 10°C for varieties ZN6, ZN7, N14 and NCo376. The error bars show that the variability in thermal to emergence of leaf tips at similar positions on the stalk increased from bottom to top of the stalk

5.2.2.3 Phyllochron gradient

The phyllochron intervals increased with each successive interval and after reaching a peak started to decrease (Table 5.5). The sudden decrease in at the end could be cause by regrowth of stalks resulting in new increased leaf appearance to sustain the regrowth. The thermal time required for the appearance of each leaf (°C day) were calculated and plotted against leaf number (Fig. 5.4). There was a high correlation between the thermal time per leaf and leaf number. Two straight lines were fitted to the data, one line up to the peak and another when the rate of leaf appearance started to increase. The slope of the best-fit line was the phyllochron gradient of each variety. The varieties had different phyllochron gradients. The low stalk population varieties (ZN6 and ZN7) had lower phyllochron gradients than high stalk population varieties (N14 and NCo376). Higher phyllochron intervals were associated with higher phyllochron gradients. Varieties ZN6 (39) and ZN7 (41), with lower phyllochron gradients produced more leaves than N14 (38) and NCo376 (37), with higher phyllochron gradients. The phyllochron interval is the inverse of the slope. The peak could be some sort of breakpoint after which leaf appearance started to increase (Fig. 5.4, Table 5.5) towards the end of the crop cycle. Variety ZN7 reached a breakpoint earlier and leaf appearance started to increase. The phyllochron gradient could be used as a parameter for modelling leaf appearance. More work would be needed to verify whether the phyllochron gradient changes for a given variety during seasonal variation and ratooning.

Table 5.5 The phyllochron intervals (°C.day) calculated using accumulated thermal time (calculated using a base temperature of 10 °C) for varieties ZN6, ZN7, N14 and NCo376

Variety	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	30 to 35	35 to 40
ZN6	34,35	63,45	84,54	114,68	149,78	168,52	158,33	66,40
ZN7	30,17	55,66	66,31	88,17	141,05	161,80	184,61	96,67
N14	35,79	54,57	71,51	106,88	158,37	196,48	165,96	28,94
NCo376	26,98	58,27	70,11	116,80	160,35	204,37	170,59	59,17

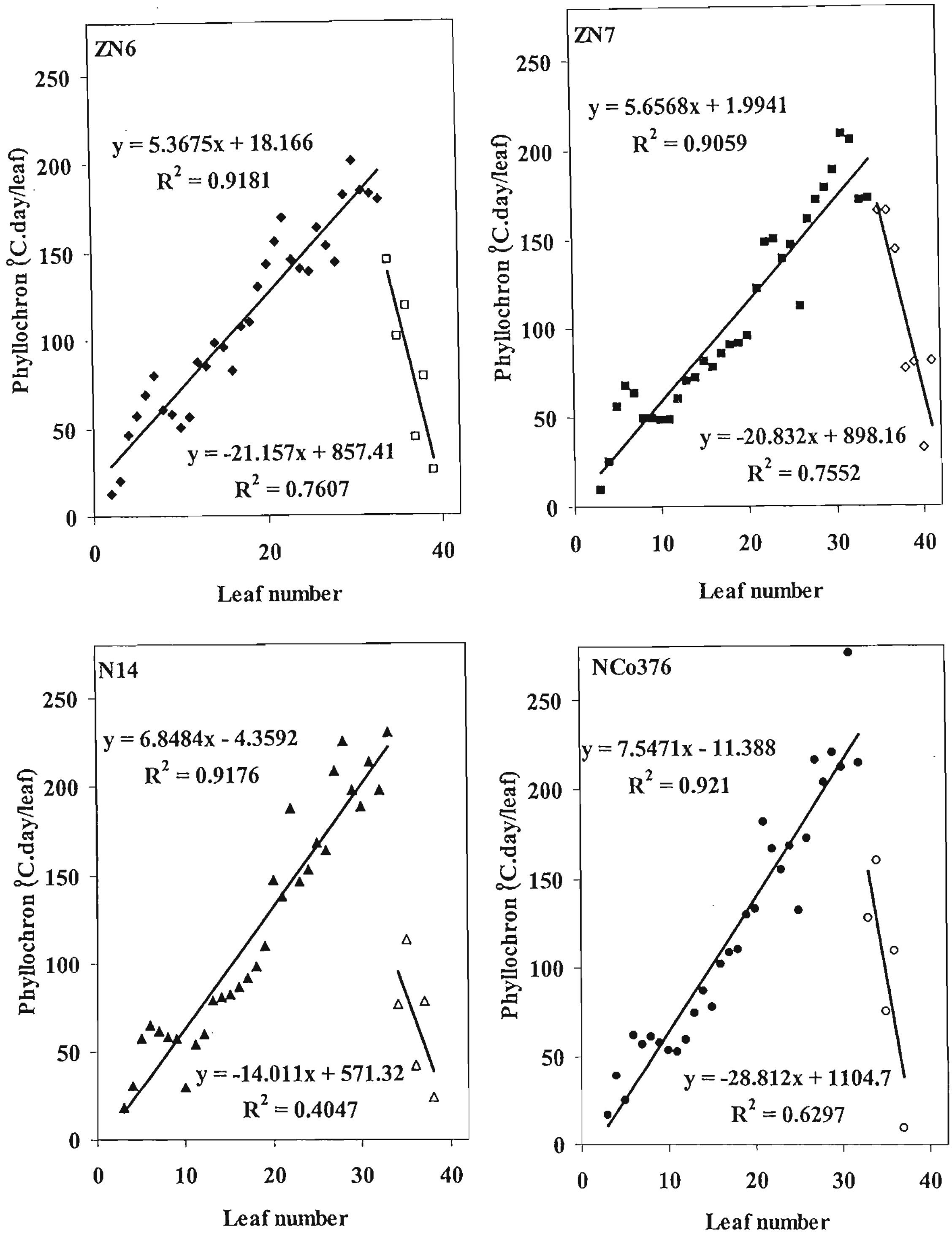

Fig. 5.4 Leaf appearance rate (°C day/leaf) for varieties ZN6, ZN7, N14 and NCo376

5.3 Tiller phenology and tiller population

5.3.1 Tiller phenology

The data showed that low stalk population varieties (ZN6 and ZN7) had lower levels of intercepted PAR required to initiate tiller senescence while higher population varieties (N14 and NCo376) required higher levels of intercepted PAR to initiate tiller senescence (Table 5.6). Variety ZN7 had significantly (P = 0,05) lower requirements of intercepted PAR (55%) required to initiate tiller senescence compared to varieties N14 and NCo376. Variety ZN7 had the lowest stalk population at harvest of 85,000. Inman-Bamber (1994b) reported cultivar PAR interception at the start of tiller senescence of 70% on ratoon crops of N12 and NCo376. The thermal time to start of tiller senescence showed no significant differences among varieties. This may mean that PAR interception was a better driver of tiller senescence than thermal time. In Section 4.3.2, it was shown that tillering was better correlated to thermal time than tiller senescence. However, the difference in thermal time was lower between experiments 1 and 2 using a base temperature of 16 °C. This suggested that 16 °C was a more likely base temperature than 10 °C. Inman-Bamber (1994b) also reported 16 °C as the base temperature of the development of tiller population of N12 and NCo376 using polynomial equations. Data by Rostron (1972) and Inman-Bamber (1994b) showed that the start of tiller senescence occurred at around 500 °C day but there were no reports of significant differences among varieties. These studies were however on ratoon crops while the data reported in this study was from a plant crop (planted on 19 October 2001), and this may explain the high values in Table 5.6. Ratoon crops emerged earlier and developed tillers faster than plant crops because of an established root system.

The low intercepted PAR at the start of tiller senescence could mean poor tolerance to low PAR of low population varieties. This could mean that low stalk population varieties are unlikely to respond to high density planting where low PAR levels sets in earlier causing tiller death. If tolerance to low PAR is genetic, some low stalk population varieties may have higher tolerance to low PAR, and these are likely to benefit from high density planting as their stalk numbers would increase therefore increasing yield. This hypothesis needs to be investigated further.

Table 5.6 The PAR interception and accumulated thermal time at the start of tiller senescence of varieties ZN6, ZN7, N14 and NCo376. The PAR intercepted is expressed as a fraction of total PAR received by the crop canopy

Variety	PAR interception at start of tiller senescence (fraction)	TT10 at start of tiller senescence (°C day)		TT16 at start of tiller senescence (°C day)	
		Exp1	Exp2	Exp1	Exp2
ZN6	0,687	1775,14	2147,25	1118.74	1355.25
ZN7	0,553	1263,95	2029,50	792.35	1279.50
N14	0,747	938,98	2029,50	938.98	1279.50
NCo376	0,749	1592,20	2029,50	1003.00	1279.50
C. V. %	15,84				
Significance	0,046	NS	NS	NS	NS

5.3.2 Tiller population

The results showed that there were highly significant differences in peak tiller population among varieties (Table 5.7). The data also showed that final tiller population (millable stalk population) and peak tiller population were correlated.

The accumulated thermal time from 50 % emergence to peak tiller population was highly variable with high coefficient of variation (C.V. %) and there were no significant differences among varieties. Inman-Bamber (1994b) reported thermal time for the peak tiller population at TT16 = 500 °C day in ratoon crops of N12 and NCo376. The high values reported in this study could be due to the fact that this was a plant crop. Inman-Bamber (1994b) reported very little variation from 500 °C day in thermal for the peak tiller population. He did not report any significant differences among varieties. Ferraris *et al.* (1994) reported that maximum stalk densities in Australian sugarcane cultivars occurred between leaf stages 7 and 15 that corresponded to a thermal time from planting of 730 to 1700 °C day with a base temperature of 15 °C. The values found in this study were within this range. In a study of ratoon crops of N12 and NCo376, Inman-Bamber (1994b), reported the tiller population of both cultivars stabilized at 1200 °C day using a base temperature of 16 °C. The high thermal time required for stable populations in this study could be because these were plant crops and developed more slowly than ratoon crops.

The thermal time required per tiller per m^{-2} to reach peak tiller population was calculated by dividing thermal time by tillers per m^{-2}. There were no significant differences between varieties (Table 5.7). High population varieties (N14 and NCo376) required less thermal time per tiller than low population varieties (ZN6 and ZN7). Variety ZN6, which reached peak tiller population later than other varieties, required the most thermal time per tiller. The thermal time per tiller could be used to determine how quickly a variety would reach peak tiller population and can therefore potentially be used as a variety parameter in modelling variety differences. The stability of the thermal time per tiller also needs to be explored further with ratoon crops and different crop starting times before its usefulness as a parameter can be ascertained.

The varieties had different ratios of final to peak tiller population and variety ZN7 had the least and NCo376 had the highest (Table 5.7). This factor could be a parameter to indicate efficiency of a variety in converting tillers produced to millable stalks. A higher ratio would be desirable. This could also be used as a parameter for predicting millable stalks per variety from peak tiller population. Higher stalk population varieties (N14 and NCo376) had higher ratios of tillers developing to millable stalks than low population varieties (ZN6 and ZN7). However, ZN7, the least stalk population variety had a higher ratio than ZN6, which produced more millable stalks. Factors affecting this ratio may need to be investigated further. The variety tolerance to low PAR transmitted could be involved in determining the ratio of final to peak tiller population.

Table 5.7 Peak and final tiller population x10^3 and thermal time (TT16) at peak tiller population of varieties ZN6, ZN7, N14 and NCo376

Variety	Peak tiller population x1000 ha^{-1}	Thermal time (TT16) to peak tiller population (°C.day)	Final tiller population x1000	Thermal time per tiller m^{-2} (peak) (°C.day tiller^{-1} m^{-2})	Ratio of final to peak population
ZN6	182,7	873,1	113,3	47,79	0,62
ZN7	150,7	576,3	97,3	38.24	0,65
N14	248,0	743,6	164,0	29.98	0,66
NCo376	265,3	774,4	181,3	29.19	0,68
C. V. (%)	11,28		17,78		
Significance	0,000	NS	0,000	NS	

5.3.3 Thermal time to start of stalk elongation

The thermal time to start of stalk elongation was calculated from 50 % shoot emergence (Table 5.8). There were no significant differences in thermal time to start of stalk elongation for varieties. The data showed that all varieties except ZN6 started stalk elongation after attaining peak tiller population. There is a need to investigate whether ratooning or crop starting times affects the start of stalk elongation of varieties.

5.4 Leaf size and leaf area index

5.4.1 Leaf size

The final area of leaves depends largely on the order in which they appear and to a lesser extent on solar irradiance and on the availability of water and nutrients (Hay and Walker, 1989). When leaf area of individual leaves was plotted against leaf number, the leaf area increased with each successive leaf on the stalk until it reached maximum and then started decreasing (Fig. 5.5). There were significant differences in the leaf area of the youngest biggest leaf among varieties and the varieties had different youngest leaf numbers that attained the maximum leaf area (Table 5.9). Variety N14 had the largest area of the biggest leaf while NCo376 had the smallest area of the biggest leaf. The leaf area of individual leaves of N14 increased linearly up to the leaf number with the biggest leaf. Inman-Bamber (1991a, 1994b) reported linear increases in leaf area of varieties N12 and NCo376. The leaf area of ZN7 decreased while the leaf area of ZN6 and NCo376 remained constant during a period of water stress. Leaf 13 and 14 of ZN7, Leaf 13 of ZN6 and leaf 11 of NCo376 were affected. Inman-Bamber (1994b) reported a decrease in leaf area for NCo376 that corresponded with a decrease in plant available soil water. The leaf areas of individual leaves of ZN6, ZN7 and NCo376 increased when soil water conditions were more favourable and this was also noted by Inman-Bamber (1994b) on NCo376. Inman-Bamber (1994b) reported that the leaves of N12 were not affected to the same extent as those of NCo376 and concluded that N12 avoided water stress better than NCo376. Similarly, ZN7 could be more susceptible to water stress than the other varieties. The large standard error of mean (SEM) could have been caused by plant-to-plant variability as 10 randomly selected plants per variety were sampled at each sampling date.

Table 5.8 The accumulated thermal time, calculated with a base temperature of 16 °C from emergence of planted eyes to start of stalk elongation of varieties ZN6, ZN7, N14 and NCo376

Variety	Accumulated thermal time to start of stalk elongation (°C.day)
ZN6	820,25
ZN7	849,75
N14	870,45
NCo376	837,25

Table 5.9 The final area of successive leaves on stalks of ZN6, ZN7, N14 and NCo376

Variety	Mean leaf number of biggest leaf	Mean leaf area of biggest leaf (cm^2)	Standard error of mean (cm^2)
ZN6	16	422,7	17,8
ZN7	18	409,6	21,7
N14	18	457,8	24,3
NCo376	15	355,3	20,7

5.4.2 Leaf area index

When LAI was plotted against days after planting and accumulated thermal time, the LAI of all varieties showed a rapid increase up to a peak and remained at around the peak only declining sharply towards end of season (Fig. 5.6). The phase of rapid increase could be associated with rapid increase in leaf area of successive leaves on the stalks, rapid leaf emergence and tillering. The leaf area then remained stabilised at the peak due to leaf expansion and most of the individual leaves attaining maximum leaf area. LAI declined towards end of the crop cycle even though leaf emergence increased because individual leaves achieved smaller leaf areas. A leaf area meter calibration error could have caused the decrease in LAI as shown in Fig. 5.6. There was a marked difference among varieties in LAI towards the peak LAI and thereafter. Variety N14 had the greatest LAI while ZN7 had the least. Towards the end of the season, ZN6 had higher LAI than NCo376 and ZN7. Low stalk population varieties (ZN6 and ZN7) reached their peak LAI earlier than high stalk population varieties (N14 and NCo376). Varieties achieved peak LAI around 2500 °C days from planting. The planting date of this crop was 19 October 2001.

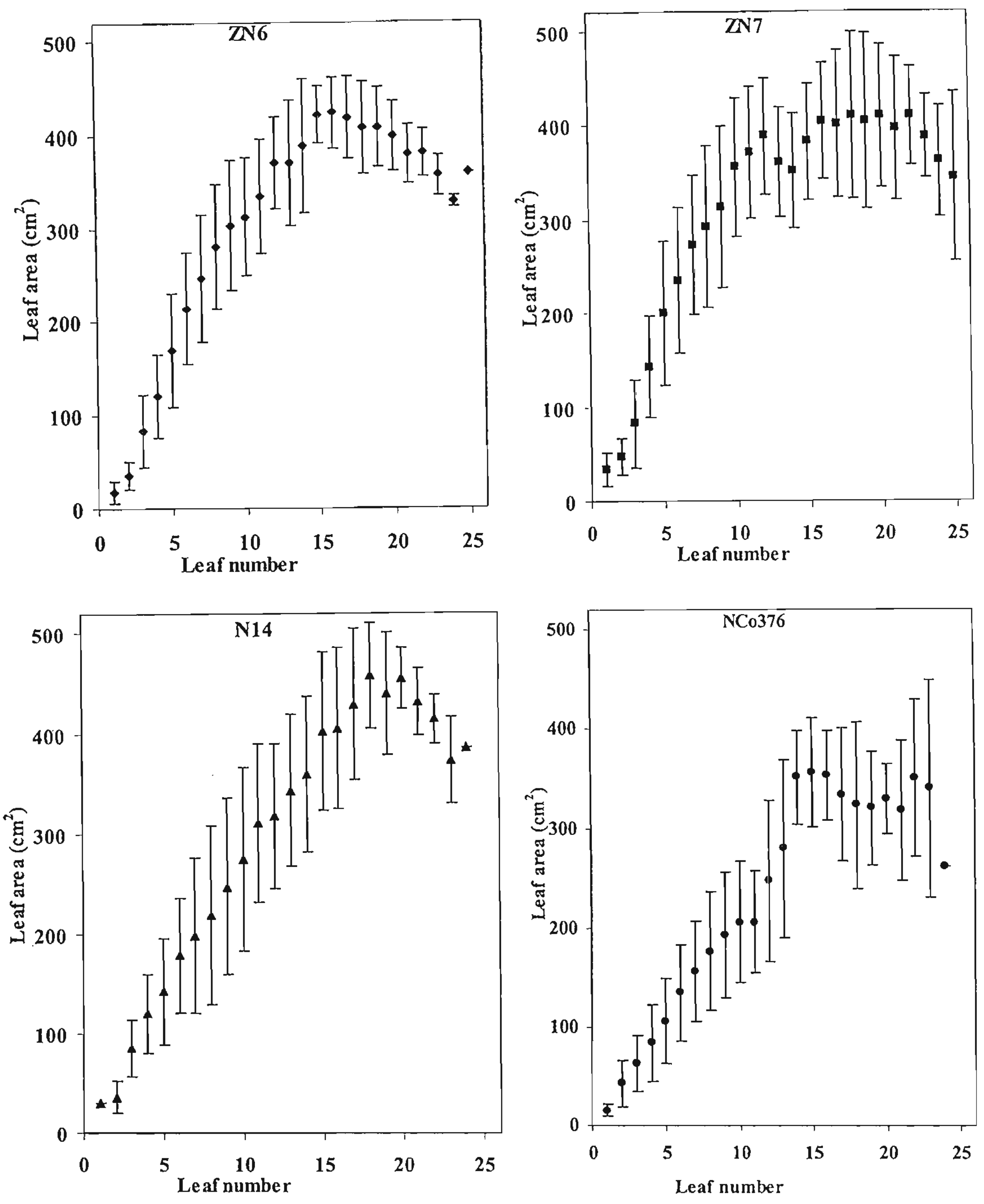

Fig. 5.5 Area of successive leaves on a stalk plotted against leaf numbers for varieties ZN6, ZN7, N14 and NCo376

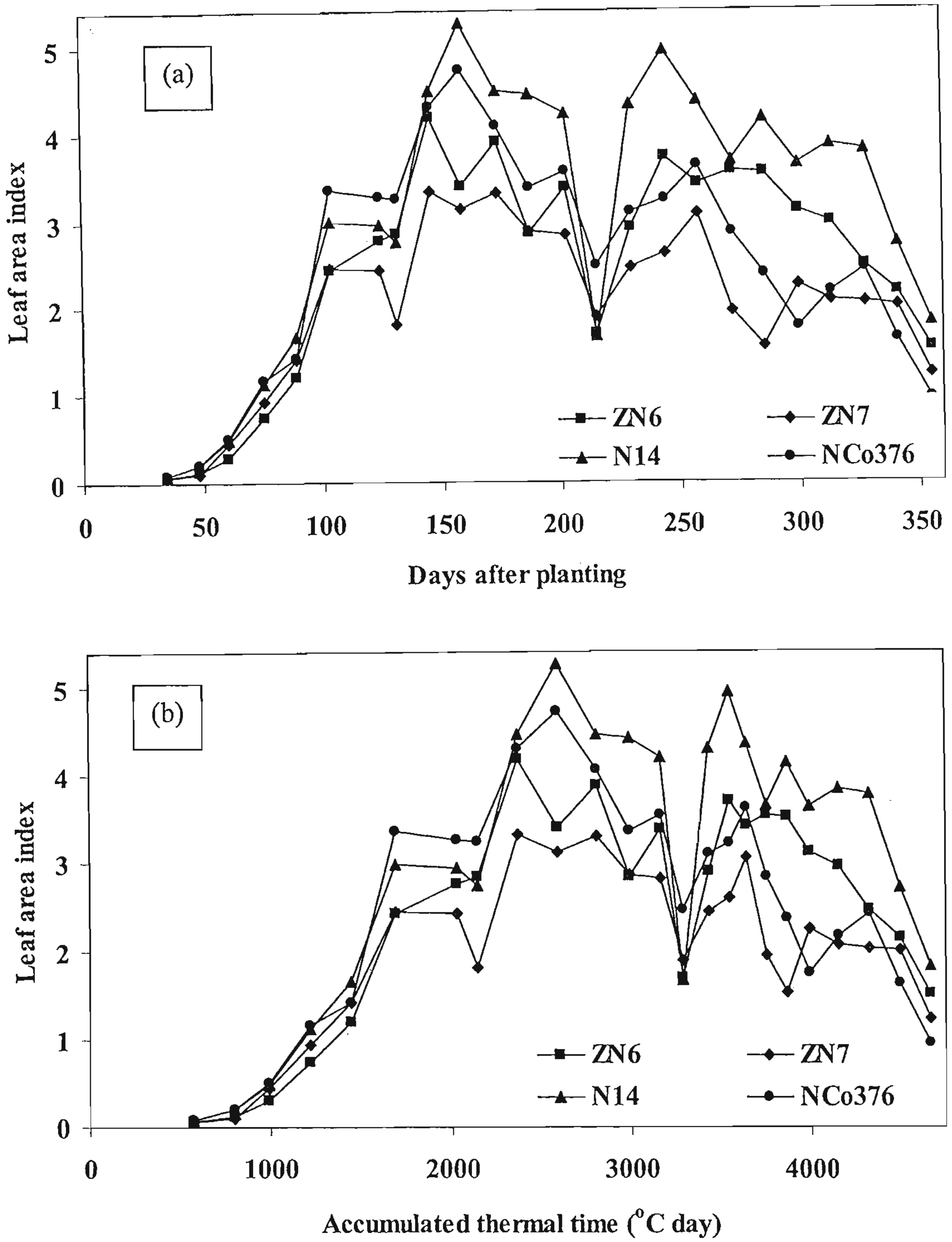

Fig. 5.6 The development of leaf area index of varieties ZN6, ZN7, N14 and NCo376 as a function of (a) days after planting and (b) accumulated thermal time calculated with a base temperature of 10 °C. The planting date was 19 October 2001

5.5 Canopy architecture

5.5.1 PAR interception

The data showed an increase in intercepted PAR with crop age for all varieties (Fig. 5.7, Table 5.10). There were highly significant differences among varieties in intercepted PAR. The data showed that high stalk population varieties (N14 and NCo376) intercepted more PAR than low stalk population varieties. The high stalk population varieties had greater LAI and therefore more leaf surface to intercept PAR (Fig 5.6). Variety N14 intercepted more PAR than the other varieties and had the highest LAI.

5.5.2 Extinction coefficients

5.5.2.1 Extinction coefficients calculated using SunScan measured LAI

The data was not significant at the 5% and 1% levels except for the 95 and 116 days after planting which were significant at 5% (Table 5.11). The data however showed that there was an increase in extinction coefficient for all varieties with increasing crop age. Variety N14 had the lowest extinction coefficient.

Table 5.10 Fraction of intercepted PAR for varieties ZN6, ZN7, N14 and NCo376

Days after planting	Fraction of intercepted PAR				Significance	Coefficient of Variation (%)
	ZN6	ZN7	N14	NCo376		
87	0,395	0,502	0,674	0,537	0,000	13.38
95	0,456	0,583	0,722	0,654	0,000	9,26
102	0,567	0,641	0,798	0,704	0,000	8,07
109	0,671	0,679	0,832	0,798	0,000	6,65
116	0,701	0,744	0,898	0,737	0,024	10,11
124	0,672	0,744	0,799	0,769	0,216	12,39
131	0,718	0,704	0,856	0,786	0,014	8,83
144	0,835	0,816	0,901	0,879	0,039	5,21
157	0,938	0,925	0,956	0,965	0,000	1,17

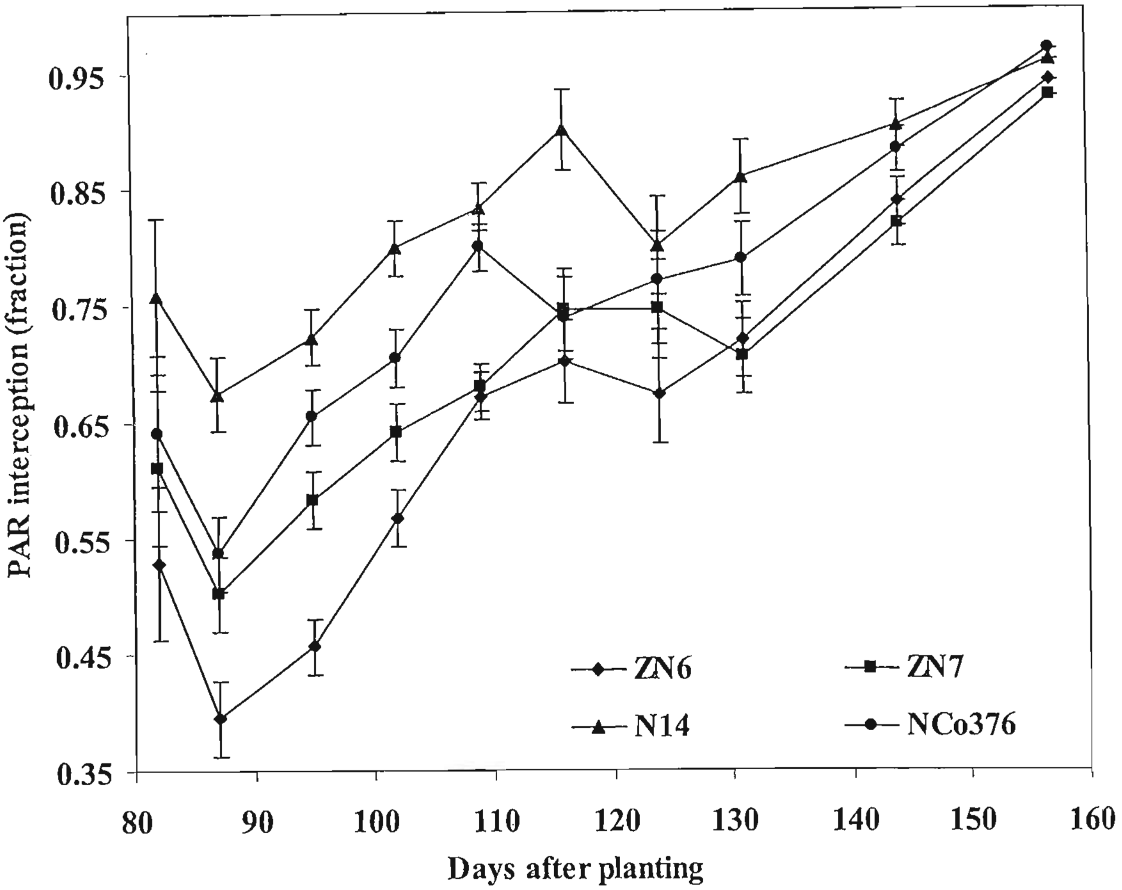

Fig. 5.7 The fraction of intercepted PAR plotted against days after planting for varieties ZN6, ZN7, N14 and NCo376. The decrease from 80 to 87 could be caused by calibration error

Table 5.11 The extinction coefficient for varieties ZN6, ZN7, N14 and NCo376 calculated using leaf area index measured with a SunScan canopy analysis system. NS means that the data was not significant

Days after planting	Extinction coefficients				Significance	Coefficient of variation (%)
	ZN6	ZN7	N14	NCo376		
87	0,447	0,478	0,471	0,482	0,244	5,95
95	0,430	0,424	0,409	0,426	0,011	2,07
102	0,493	0,497	0,488	0,502	NS	3,39
109	0,559	0,571	0,582	0,584	NS	6,48
116	0,675	0,640	0,597	0,662	0,026	4,80
124	0,539	0,699	0,537	0,562	0,250	23,70
131	0,588	0,607	0,571	0,609	0,394	6,50

5.5.2.2 Extinction coefficient calculated using Delta-T measured LAI

Most of the data was not significant at the 5% and 1% levels except for 103 days after planting which was significant at 5% (Table 5.12). The data was variable with a high coefficient of variation. The high variability in the data could be attributed to the fact that the LAI was measured at a different location to the intercepted PAR. The data showed an increase in extinction coefficient with increasing age of the crop. Many models overlook this and this needs to be incorporated into the models (Inman-Bamber, 1991a, 1004b; Keating *et al.*, 1999)

5.5.2.3 Extinction coefficient determined from graphs of ln (L_t/L_o) and LAI

A natural log transformation was done on the transmitted fraction of PAR (L_t/L_o). The data was plotted with LAI on the *x*-axis and ln(L_t/L_o) on the *y*-axis for Delta-T measured LAI (Fig. 5.8) and SunScan measured LAI (Fig. 5.9). A best line fit and the equation of the best line fit were applied to the data. The coefficient of –x was the extinction coefficient (Table 5.13). The extinction coefficients obtained using SunScan LAI were higher and more similar to findings of Inman-Bamber (1994b) while those derived from Delta-T LAI were lower and similar to values reported by Chiroro (1999). Chiroro (1999) used a similar Delta-T leaf area meter used in this study. Leopold and Kriedemann (1975) reported that PAR interception within a canopy was closely related to LAI. They also reported that in vertical leaves extinction coefficients ranged between 0,3 and 0,5 while horizontal leaves had 0,7 to 1,0. In this study ZN7 had more horizontal leaves than the other varieties and higher extinction coefficients. There were however lower R^2 values between the transmitted PAR and Delta-T LAI when compared to the R^2 of transmitted PAR and SunScan LAI. This could be attributed to the fact that with the SunScan, the transmitted PAR and LAI are measured on the exact same position and at the same time while the Delta-T LAI was determined destructively from an adjacent position from which transmitted PAR was measured. This may mean the extinction coefficients could be more accurately determined using SunScan measurements alone. Variety N14 had the lowest extinction coefficient while ZN6 had the highest.

Table 5.12 The extinction coefficient of varieties ZN6, ZN7, N14 and NCo376 calculated using leaf area index measured with a Delta-T leaf area meter. NS means that the data was not significant

Days after planting	Extinction coefficient				Significance	Coefficient of variation (%)
	ZN6	ZN7	N14	NCo376		
89	0,431	0,510	0,753	0,564	0,098	33,53
103	0,356	0,460	0,558	0,369	0,026	22,89
124	0,407	0,651	0,613	0,483	0,248	37,66
131	0,447	0,759	0,772	0,488	0,065	35,42
145	0,439	0,528	0,581	0,565	NS	34,84
158	0,808	0,876	0,627	0,735	0,090	18,92

5.5.3 Leaf angles

There were significant differences ($P=0,05$) in leaf angles among varieties (Fig. 5.10). Variety ZN7 had the largest leaf angles while NCo376 had the smallest leaf angles. The leaf angles remained constant throughout the crop cycle. The leaf angle could be used to determine the level of leaf shading in a canopy. Wider leaf angles are likely to shade each other and result in poor PAR penetration. Upright leaves would allow more PAR penetration and have a lower corresponding extinction coefficient but result in late canopy closure as opposed to horizontal leaves. Varieties N14 and NCo376 with narrower leaf angles had lower extinction coefficients (Table 5.12).

Table 5.13 The extinction coefficient for varieties ZN6, ZNN7, N14 and NCo376 determined from the best line fit of LAI and ln (L_t/L_o)

Variety	Delta-T LAI		SunScan LAI	
	k	R^2	k	R^2
ZN6	0,4734	0,4876	0,5752	0,8727
ZN7	0,4265	0,4787	0,5398	0,8700
N14	0,3356	0,4114	0,5315	0,8685
NCo376	0,3805	0,4664	0,5414	0,8422

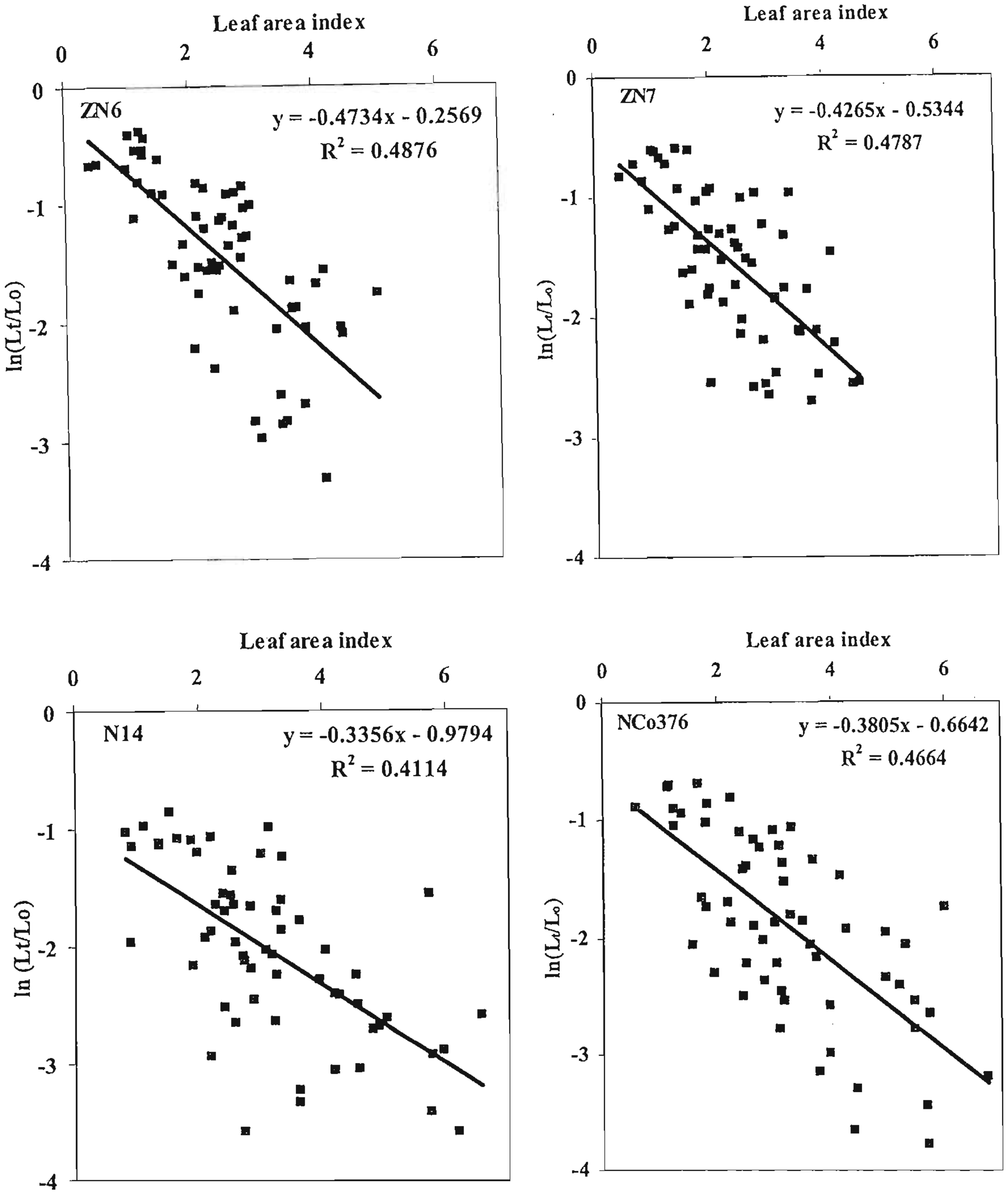

Fig. 5.8 The ln (L_t/L_o) plotted against leaf area index measured using Delta-T leaf area meter. The coefficient of -x is the extinction coefficient

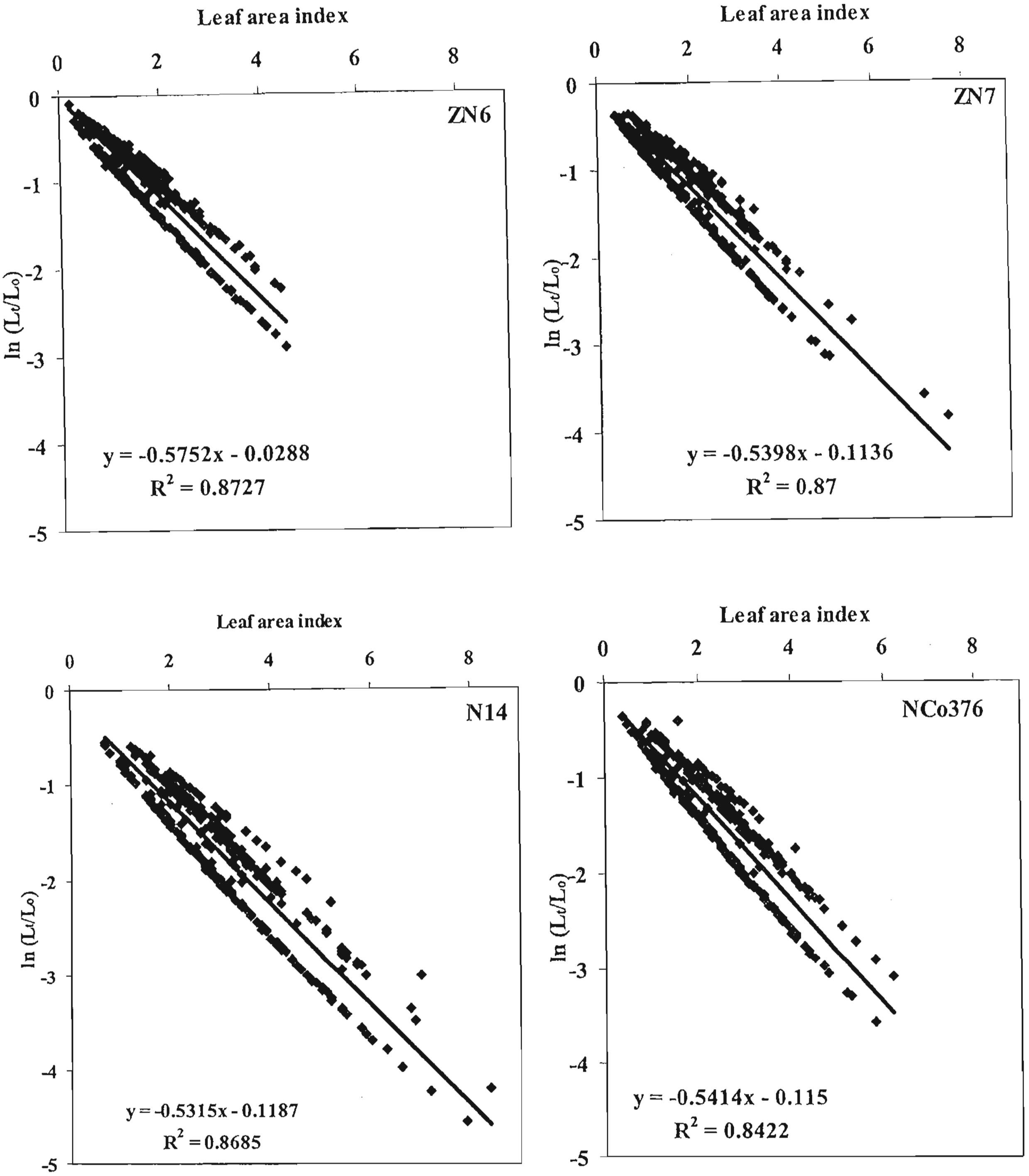

Fig. 5.9 The ln (L_t/L_o) plotted against leaf area index measured using SunScan ceptometer. The coefficient of -x is the extinction coefficient

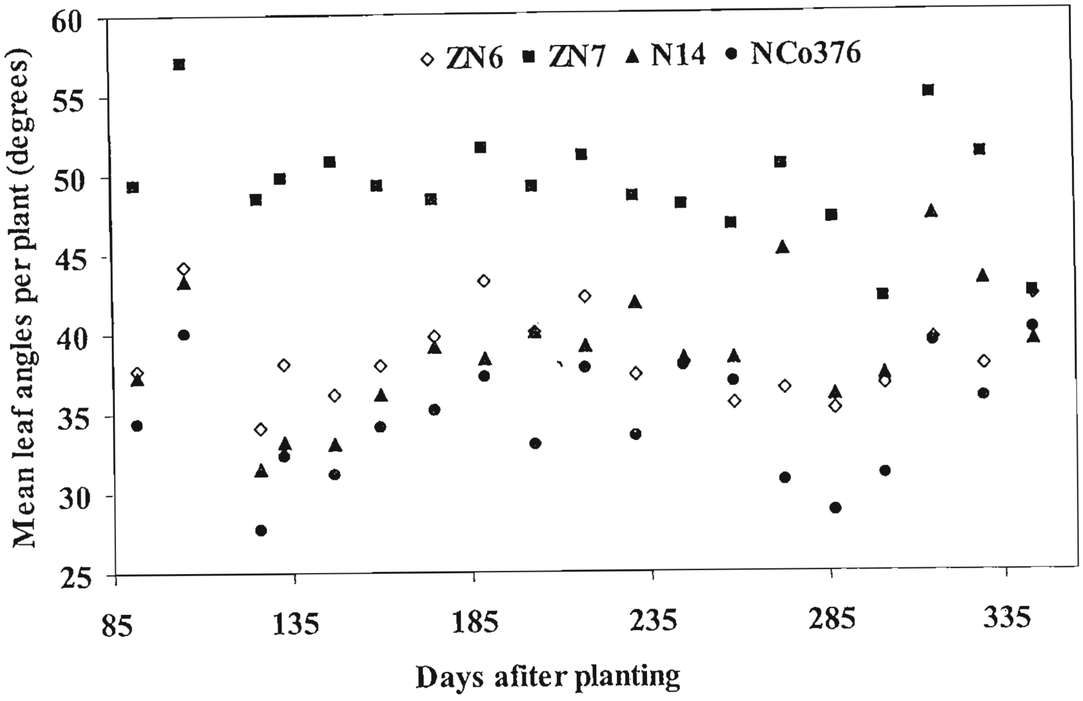

Fig. 5.10 The mean leaf angle of varieties ZN6, ZN7, N14 and NCo376 as a function of days after planting

5.5.4 Ellipsoidal leaf angle distribution parameter (ELADP)

The term ELADP describes the spherical distribution of leaves in the crop canopy and determines the distribution of PAR in the plant canopy (Potter *et al.*, 1996). There were significant differences in ELADP (P = 0,01) in ELADP among varieties and ZN7 had the highest ELADP value for all varieties tested while NCo376 had the lowest. This meant that ZN7 had more horizontal leaves than the other varieties. A higher ELADP means that PAR distribution within the plant canopy could be poorer due to leaf shading. The value of ELADP was an input factor in determining leaf area index using the SunScan Canopy Analysis System. The value remained stable throughout the crop cycle (Fig. 5.11).

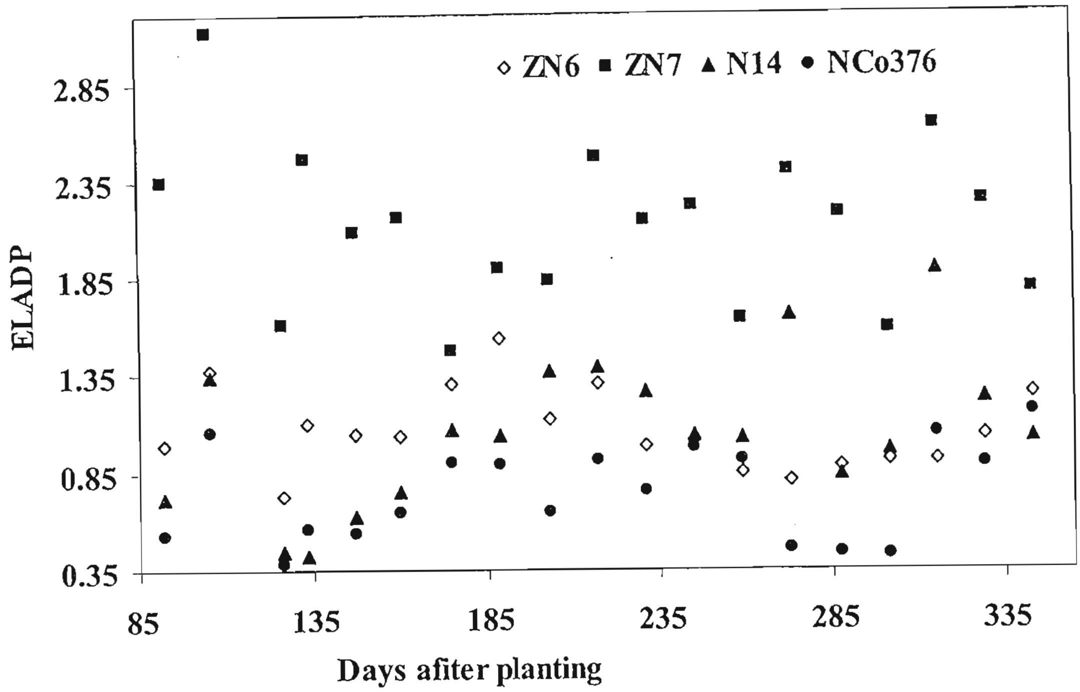

Fig. 5.11 The mean ELADP values for varieties ZN6, ZN7, N14 and NCo376 plotted as a function of days after planting

5.6 General discussion

In summary, the most notable variety differences in canopy development were:

- N14 had the highest rate of shoot emergence and ZN6 had slowest rate
- ZN7 had the highest rate of leaf appearance
- N14 had the largest, and NCo376 the smallest leaves
- Tiller senescence commenced the earliest in ZN7 and the latest in ZN6.
- Tiller population was the highest in NCo376 and lowest in ZN7
- There were variety differences in proportion of millable stalks to peak tiller population.

Generally this implied that ZN7 produced relatively large leaves at a faster rate compared to other varieties. ZN7 produced few tillers because tiller senescence started earlier than for example that of NCo376, which can be regarded as a high tillering variety. The impact of these characteristics on crop canopy (LAI) and PAR interception is shown in Figs 5.5 and 5.6. Variety N14 had the greatest LAI after canopy cover or LAI of 3. Variety N14 also intercepted the largest proportion of incident PAR followed by NCo376 (Fig. 5.6). Variety N14 had the lowest extinction coefficient.

Biomass production is dependant on the amount of PAR intercepted by the canopy (Singels and Donaldson, 2000). Therefore varieties that can intercept more PAR should have the desirable characteristic for producing high biomass yields and therefore high cane yields.

Varieties N14 and NCo376 intercepted more PAR than ZN6 and ZN7. The difference between these varieties is that N14 and NCo376 are high population varieties while ZN6 and ZN7 are low population. Variety N14 had large leaves but NCo376 had small leaves and this could mean that leaf size is less important in PAR capture than stalk population. Varieties ZN6, N14 and NCo376 had similar leaf angles and ELADP values, but they intercepted PAR differently, and therefore canopy architecture could be less important in PAR interception than stalk population. Therefore the role of leaf size and canopy architecture does not seem that important in PAR capture and tiller population could be the most important character determining PAR interception and possibly biomass production. This could mean that selecting for high tillering in breeding programmes could be the key to achieving high yields. High density planting aimed at increasing tiller population could also hold the key to increasing yield by increasing PAR capture. Work done in Australia by Bull and Bull, (1996 and 2000) and Bull and Mcleod (2000) has shown there could be potential in increasing yield using high density planting. Further research is needed to explore these potentials. The effect of high density planting on the ratio of millable stalks to peak tiller population may also need further investigation.

Future work would need to focus on measuring the parameters defined here for more varieties, in more environments and for ratoon crops. We suspect that some of these parameters are well correlated and data should be investigated for these links in future work. For example the commencement of tiller senescence and rapid stalk elongation could coincide, while characteristics such as tillering proficiency and leaf size could also be linked. An attempt could also be made to categorize varieties in groups with sets of similar parameters and to identify easily recognizable morphological or physiological attributes for each category. Categorization of varieties has been attempted by Inman-Bamber (1994b).

5.7 Conclusions

A base temperature of 16 °C for shoot emergence was more likely as it had the least difference in shoot emergence between two experiments.

The varieties had different leaf sizes and youngest leaves that attained maximum leaf area. Variety N14 had the largest leaves and the highest LAI.

The data showed that the gradual increase from early to later leaves provided a better estimation of thermal time requirements for leaf emergence than the broken stick equation. The phyllochron gradients could be a variety parameter for modelling leaf appearance.

The data showed that low stalk population varieties (ZN6 and ZN7) had lower levels of intercepted PAR required to initiate tiller senescence while higher population varieties (N14 and NCo376) required higher levels of intercepted PAR to initiate tiller senescence. Therefore high tillering could be more important for PAR interception than canopy architecture and leaf size. The extinction coefficients increased with crop age but there were no significant differences among varieties.

The variation in PAR transmitted at the start of tiller senescence could be indicating the possibility of variety differences. If there are genetic differences in tolerance to PAR transmitted to bottom of canopy, then certain varieties with low tolerance are unlikely to have a yield respond to high density planting while those with high tolerance will show greater yield increases with high density planting. Therefore future work may need to verify this fact as it offers an opportunity of increasing yield through high density planting.

From the analysis of physiological parameters for canopy development, variety N14 emerged the best variety. Its planted eyes emerged faster and achieved higher percent of emergence of planted eyes and that was desirable for cane establishment. Its area of leaves increased linearly with successive leaves and it achieved the greatest leaf area that was desirable for increased PAR interception and photosynthetic capacity. The fast appearance of bottom leaves on the stalks increased photosynthetic area, PAR interception and shaded weeds while leaf appearance slowed later when a large leaf area had been produced. Its tillers started senescing at low transmitted PAR threshold and therefore produced a higher stalk population.

Chapter 6: EVALUATION OF CANEGRO VERSION 1 AND VERSION 2 CANOPY MODELS

6.1 Introduction

One of the important requirements to be met before a crop simulation model can be employed for decision-making is to verify that the model is technically correct for the given task (Rasmussen, 1991). Models are, however, by their nature simplifications of the real world, and therefore the technical correctness of a model is hard to define (MacRobert, 1993). The process of evaluating the suitability of a model for a given task has been termed validation and may be defined as the comparisons of predictions of a verified model with experimental observations other than those used to build and calibrate the model, and the identification and correction of errors in the model until it is suitable for its intended purpose (Whisler *et al.*, 1986). This definition clearly states the need for independent data sets on which to validate models. It also encompasses the evolutionary nature of modelling and the need or opportunity for continual improvement of model content and performance (MacRobert, 1993; MacRobert and Savage, 1998).

6.2 Statistical methods to evaluate model performance

In order to verify and calibrate a model some sort of criterion is needed to evaluate model performance. It is generally accepted that the ultimate test of a simulation model is the accuracy with which it describes the actual system, thus comparing the simulated with observed data (Willmott, 1982; Jones and Kiniry, 1986). Du Toit (1995) noted that a number of statistical methods to analyse model performance were available, for example, linear regression techniques as proposed by Jones and Kiniry (1986) and Flavella (1992), D-index, systematic and unsystematic mean square errors as proposed by Willmott (1982). MacRobert (1993) followed the procedures described by Willmott (1982) while Savage (1998a) reviewed similar procedures. Willmott (1981) suggested the use of the coefficient of variation of the observed and predicted values as an indication of the model's ability to mimic the variability inherent in the observed data set.

6.2.1 Linear regression

Jones and Kiniry (1986) used linear regression techniques of the form $y = a + bx$ with observed results as the independent variable. Good model performance was obtained when the intercept (a) approached zero and the slope of the regression approached unity, indicating a near perfect relationship between observed and simulated values. Complementary to this regression, the Pearson correlation coefficient (R) can also be calculated, indicating the similarity or inverse similarity of a response in y for a response in x. From R the coefficient of determination (R^2) can be obtained, signifying the percentage of change predicted. Savage (1998a) warned against the use of correlation coefficients if the data are not randomly distributed as that introduces bias. The disadvantages of using R^2 are that it is dependent on number of observations and does not distinguish between systematic and unsystematic bias. Unsystematic error describes random and unbiased error and a higher systematic error relative to unsystematic error was in favour of better model development as the bias could be fixed by fixing the model. Systematic errors are biased and non-random and good model performance is indicated by the systematic errors approaching zero.

The deficiencies of the latter statistical parameters were pointed out by Willmott (1982) and Harrison (1990) who indicated that the observed and simulated data may occur in a narrow band, whereas this is usually not the case with the coefficients. Secondly, it is difficult to identify the point when a model is valid or not valid.

6.2.2 MAE, MRAE, RMSE, RMSEs, RMSEu and D-index

Mean absolute error (*MAE*) and mean relative absolute error (*MRAE*) are some statistics used for comparing observed and predicted data. The *MAE* and *MRAE* provide a direct comparison between observed and predicted data. The *D*-index (index of agreement), *RMSEs* (root mean square error systematic), *RMSEu* (root mean square error unsystematic) and *RMSE* (root mean square error) are parameters, which Willmott (1982) recommended for model evaluation. *RMSEs* and *RMSEu* are measures of statistical bias, representing systematic and unsystematic bias respectively. Lower *RMSEs* indicate good model performance. Due to limitations in the use of correlation coefficients as an agreement index, Savage (1993) stated that the statistics as defined by Willmott (1982) should be used as a standard for model evaluation.

According to Willmott (1982) a good model's *D*-index should approach unity and the *RMSEs* zero, whereas *RMSEu* should approach *RMSE*. Low values for *MAE* and *MRAE* show that the model simulations are closer to measured data.

$$MAE = n^{-1}\sum_{i=1}^{n}(P_i - O_i) \qquad 6.1$$

$$MRAE = n^{-1}\sum_{i=1}^{n}[(P_i - O_i)/O_i] \qquad 6.2$$

$$RMSE = [n^{-1}\sum_{i=1}^{n}(P_i - O_i)^2]^{0.5} \qquad 6.3$$

The *MAE, MRAE* and *RMSE* are among the best overall measures of model performance, as they summarise the mean difference in the values of observed (O_i) and predicted (P_i) (Willmott, 1982).

$$RMSEs = [n^{-1}\sum_{i=1}^{n}(\hat{P}_i - O_i)^2]^{0.5} \qquad 6.4$$

$$RMSEu = [n^{-1}\sum_{i=1}^{n}(P_i - \hat{P}_i)^2]^{0.5} \qquad 6.5$$

$\hat{P}_i$ is regarded as the best estimate of the predicted quantity (Savage, 1993) calculated with the intercept (a) and slope (b) of the least-squares regression of P_i on O_i, $\hat{P}_i = a + bO_i$ (Willmott, 1982). The advantage of *RMSEs* is that it indicates the bias (deviation of the actual slope value from the 1:1 line) in a particular model, compared with the random variation (*RMSEu*) that may occur (Savage, 1993). Willmott (1982) proposed an index of agreement of the form

$$D = 1 - [\sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}(P_i' - O_i')^2] \qquad 6.6$$

where $P_i' = P_i - \overline{O}$ (average of the observed) and $O_i' = O_i - \overline{O}$. The index is intended to be a descriptive measure, and it is both a relative and bounded measure that can be applied in order to make cross-comparisons between models (Willmott, 1982).

6.2.3 Standard deviation and coefficient of variation

The comparisons of the standard deviation (std) and coefficient of variation (C.V.) of observed data against predicted data is a way of determining if the model predictions have the same variations as the observed data. The closer the standard deviation and coefficient of variation of observed and predicted data is to zero, the more accurate the model is in modelling the processes under study. These values can be used to compare the ability of the model to predict performance of varieties. The varieties where the values of predicted and observed are closer, it can be assumed that the model is well calibrated for those varieties.

6.2.4 Observed versus simulated graphs

Observed versus simulated graphs, also known as 1:1 graphs are widely used in simulation evaluations (Willmott, 1982; Jones and Kiniry, 1986; Mugabe, 1995). Harrisson (1990) recommended that whatever statistical method is used it is appropriate to combine it with the 1:1 graphs, since it may be particularly helpful in identifying the pattern of differences between the predicted and observed values. Willmott (1981) recommended that data plots accompany any comparisons between observed and simulated variables, as graphic aids lends visual credibility to quantitative comparisons as well as pointing out possible erroneous computations.

6.2.5 Time series graphs

Time series graphs are graphs plotted for the development and growth of the measured parameter with time. If the model predicted values are plotted on the same graph with measured data, it would point out the points when the model does not agree with measured data. This would help in identifying the stages of development on the lifecycle of a crop where the model performance is poor and needs calibration.

6.3 Model parameters

6.3.1 CANEGRO canopy model version 1 parameters

This canopy model is as described in Inman-Bamber (1994b) and was calibrated with variety specific leaf parameters (Table 6.1) obtained in this study (Chapter 5) but no tiller parameters. This is the canopy model in the CANEGRO model without variety parameters.

Table 6.1 Variety parameters used in canopy model version 1

Parameter	ZN6	ZN7	N14	NCo376
Maximum leaf size (cm^2)	420	410	460	360
First leaf to reach maximum size	16	18	18	14
Phyllochron 1 (Tbase = 10 °C) (°C.day)	79	69	69	69
Phyllochron 2 (Tbase = 10 °C) (°C.day)	169	169	169	169
Phyllochron switch (leaf number)	14	18	18	18
Maximum number of green leaves per stalk	13	13	13	12

6.3.2 CANEGRO canopy model version 2 parameters

This canopy model is based on leaf parameters obtained in this study (Chapter 5) and a simple improved empirical function for tiller population. This empirical version has both leaf and tiller parameters (Singels, 2003, personal communication). The tiller parameters included are peak tiller population, thermal time to peak tiller population and rate of tiller senescence (Table 6.2). This is an improved version of the CANEGRO canopy model version 1 which is the version used by the current CANEGRO model. These improvements were on the parameters for modelling of variety differences in canopy growth and development. The equations in the models are as described in section 2.8.

6.4 Model evaluation

6.4.1 Introduction

The above statistical and graphical methods of evaluating the model-simulated data against measured data were used for verification of the models for varieties ZN6, ZN7, N14 and NCo376. These methods were applied to tiller heights, tiller population, leaf area index, green leaf numbers per stalk, dead leaf numbers per stalk and intercepted PAR. The data used to calibrate the various components are used for evaluation.

Table 6.2 Variety parameters used in canopy model version 2

Parameter	ZN6	ZN7	N14	NCo376
Maximum leaf size (cm^2)	420	410	460	360
First leaf number to reach maximum size	16	18	18	14
Phyllochron 1 (Tbase = 10 °C) (°C.day)	79	69	69	69
Phyllochron 2 (Tbase = 10 °C) (°C.day)	169	169	169	169
Phyllochron switch (leaf number)	14	18	18	18
Maximum number of green leaves per stalk	13	13	13	12
Peak tiller population (stalks m^{-2})	15	11,95	20,5	23
Thermal time to peak tiller population (T_b=16 °C) (°C.day)	690	680	720	580
Relative tiller senescence rate (stalk $stalk^{-1}$)	0,001	0,001	0,001	0,001

6.4.2 Tiller height

The model evaluation statistics (Table 6.3) showed that CANEGRO version 2 simulated the tiller heights better than version 1. The means of tiller heights predicted with version 2 were closer to the mean of observed values for all varieties. The MAE and RMSE for version 2 were lower than those for version 1. The D-index for version 2 was higher than that for version 1 indicating better agreement between observed and predicted tiller heights. The RMSEs and RMSEu were high in both versions but relatively lower for version 2 than version 1. There were higher RMSEs than RMSEu in varieties ZN6 and ZN7 in version 1 while ZN7 had higher RMSEs than RMSEu in version 2. The models overestimated tiller heights early in the growth cycle and underestimated thereafter (Figs 6.1 and 6.2) and this resulted in high systematic errors. The slope, intercept and R^2 of the predicted versus observed showed no differences between version 1 and version 2 (Fig. 6.2). The minimum and maximum values of observed and predicted tiller heights were very close while observed tiller heights were more variable than predicted tiller heights (Table 6.3).

Table 6.3 Evaluation of CANEGRO canopy models version 1 (V1) and version 2 (V2) in predicting the tiller heights (m) of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	1,749		1,864		1,701		1,795	
Mean P	1,589	1,726	1,578	1,724	1,576	1,692	1,576	1,685
MAE	0,221	0,180	0,323	0,236	0,211	0,195	0,280	0,239
MRAE	0,168	0,238	0,209	0,256	0,180	0,271	0,210	0,294
RMSE	0,272	0,215	0,378	0,272	0,248	0,216	0,329	0,271
RMSEs	0,202	0,117	0,330	0,203	0,139	0,186	0,175	0,173
RMSEu	0,182	0,181	0,184	0,181	0,201	0,202	0,396	0,209
D-index	0,975	0,984	0,955	0,976	0,979	0,984	0,964	0,975
b	0,865	0,875	0,830	0,845	0,851	0,851	0,857	0,854
a	0,077	0,197	0,028	0,149	0,246	0,128	0,037	0,152
R^2	0,950	0,952	0,948	0,958	0,958	0,958	0,933	0,932
n	24	24	24	24	24	24	24	24
Maximum O	2,778		2,996		2,850		2,691	
Maximum P	2,841	2,984	2,824	2,981	2,824	2,939	2,824	2,930
Minimum O	0,116		0,110		0,117		0,101	
Minimum P	0,090	0,203	0,090	0,203	0,090	0,203	0,090	0,203
Std O	0,935		0,966		0,948		0,928	
Std P	0,829	0,838	0,824	0,837	0,824	0,823	0,824	0,821
C.V. % O	53,44		51,83		55,71		51,72	
C.V. % P	52,17	48,54	52,27	48,54	52,27	48,66	52,27	48,73

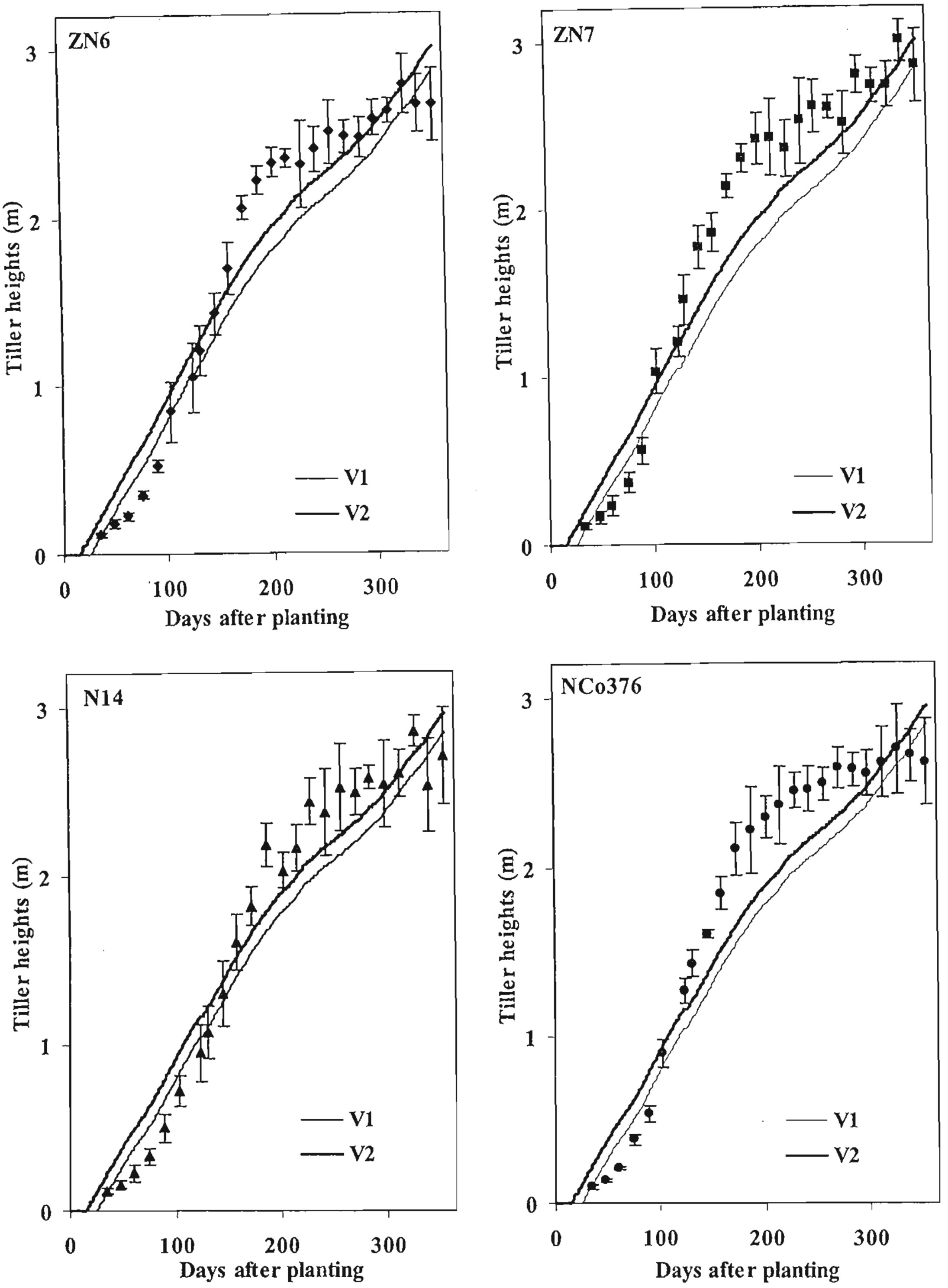

Fig 6.1 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for tiller heights of varieties ZN6, ZN7, N14 and NCo376

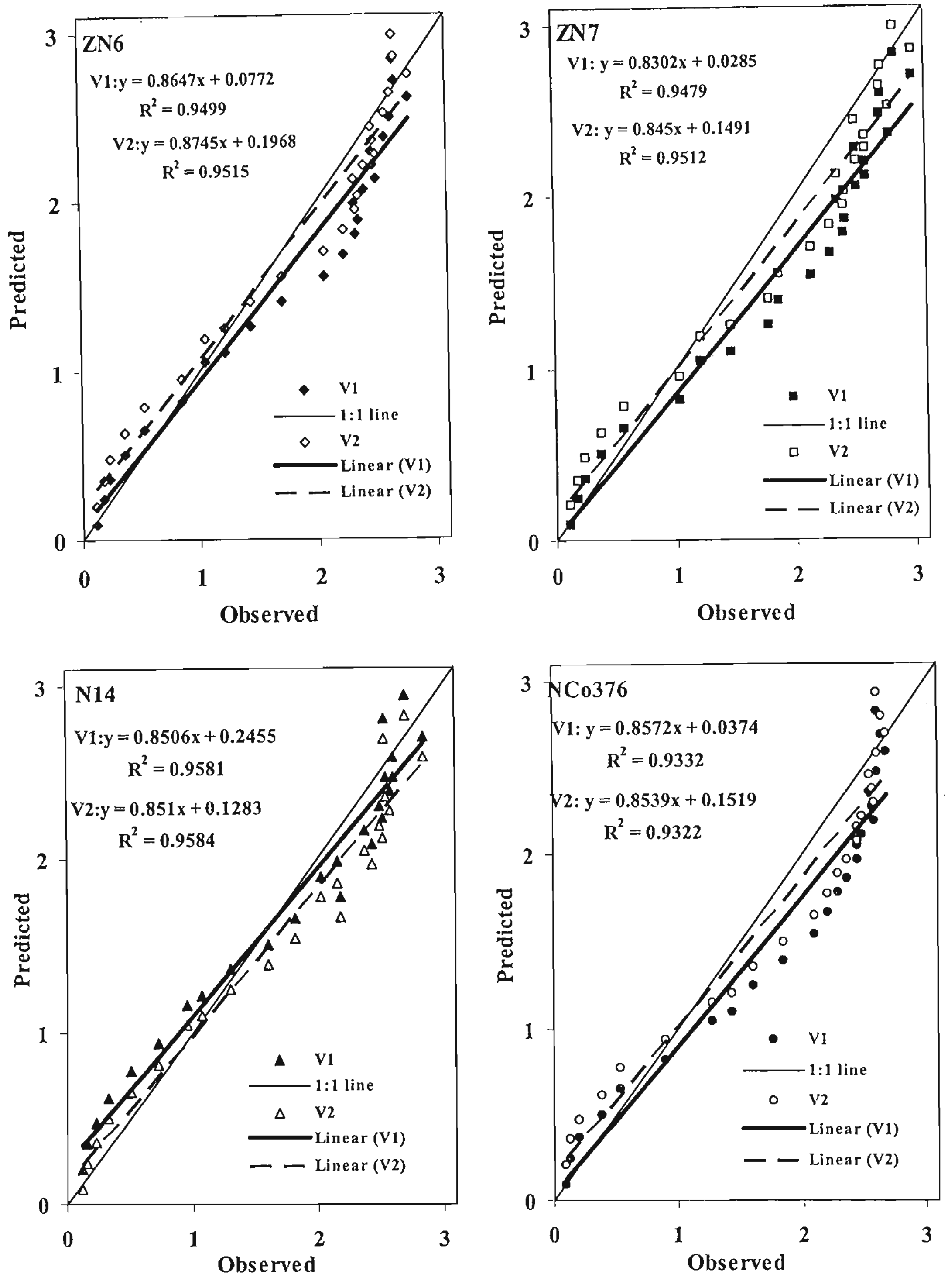

Fig 6.2 Predicted versus observed tiller heights (m) of varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.3 Tiller population

The modelling of stalks m^{-2} except for variety N14 was greatly improved with version 2 models compared to version 1. The means of observed and predicted stalks m^{-2} were closer while the MAE, MRAE and RMSE were lower for version 2 than version 1 showing that version 2 is better than version 1. The D-index of version 2 (except for N14) was higher than that for version 1. Varieties ZN6 and ZN7 showed higher RMSEs than RMSEu in both version 1 and version 2 while N14 and NCo376 had higher RMSEs than RMSEu in version 1 and lower RMSEs than RMSEu in version 2. The systematic errors in stalk population of the version 2 were better in varieties N14 and NCo376 than ZN6 and ZN7 (Fig 6.3). Version 1 model was out of phase with stalk population development of all the varieties while version 2 was very close to NCo376, overestimated the stable tiller population of ZN6 and ZN7 and underestimated the tiller senescence of N14 (Fig. 6.3). The slope of the predicted versus observed (except NCo376), intercept (except ZN7 and NCo376) and R^2 (except ZN7) increased, decreased and increased from version 1 to version 2 (Fig. 6.4). The minimum and maximum, and variation of the observed and predicted stalks m^{-2} data were closer in the version 2 model (Table 6.4).

Table 6.4 Evaluation of CANEGRO canopy model version 1 (V1) and version 2 (V2) in predicting the tillers m^{-2} of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	10,967		8,994		13,528		16,839	
Mean P	14,432	12,886	14,473	11,062	14,473	15,827	14,473	17,060
MAE	3,929	2,454	5,478	2,708	2,126	3,227	2,689	1,587
MRAE	0,388	0,248	0,613	0,320	0,162	0,268	0,153	0,102
RMSE	4,782	2,880	6,084	2,953	2,597	3,664	3,376	2,240
RMSEs	3,643	2,109	5,549	2,150	2,742	1,288	2,503	1,040
RMSEu	3,098	1,962	2,495	2,024	2,703	2,850	2,265	1,984
D-index	0,508	0,673	0,391	0,411	0,851	0,683	0,796	0,872
b	0,559	0,658	1,585	0,622	0,578	0,753	0,765	0,708
a	8,298	5,676	3,997	5,464	8,013	4,286	1,598	5,145
R^2	0,175	0,421	0,490	0,187	0,414	0,583	0,579	0,606
n	24	24	24	24	24	24	24	24
Maximum O	16,400		12,400		20,933		22,667	
Maximum P	22,101	15,238	22,345	12,063	22,345	20,609	22,345	22,879
Minimum O	5,333		5,333		6,000		6,933	
Minimum P	6,426	3,735	6,426	3,167	6,426	4,966	6,426	6,332
Std O	2,601		1,595		3,616		3,551	
Std P	3,483	2,635	3,567	2,294	3,587	3,245	3,567	3,228
C.V. % O	23,72		17,74		26,73		21,09	
C.V.% P	24,14	20,45	24,65	20,74	24,65	20,50	24,65	18,92

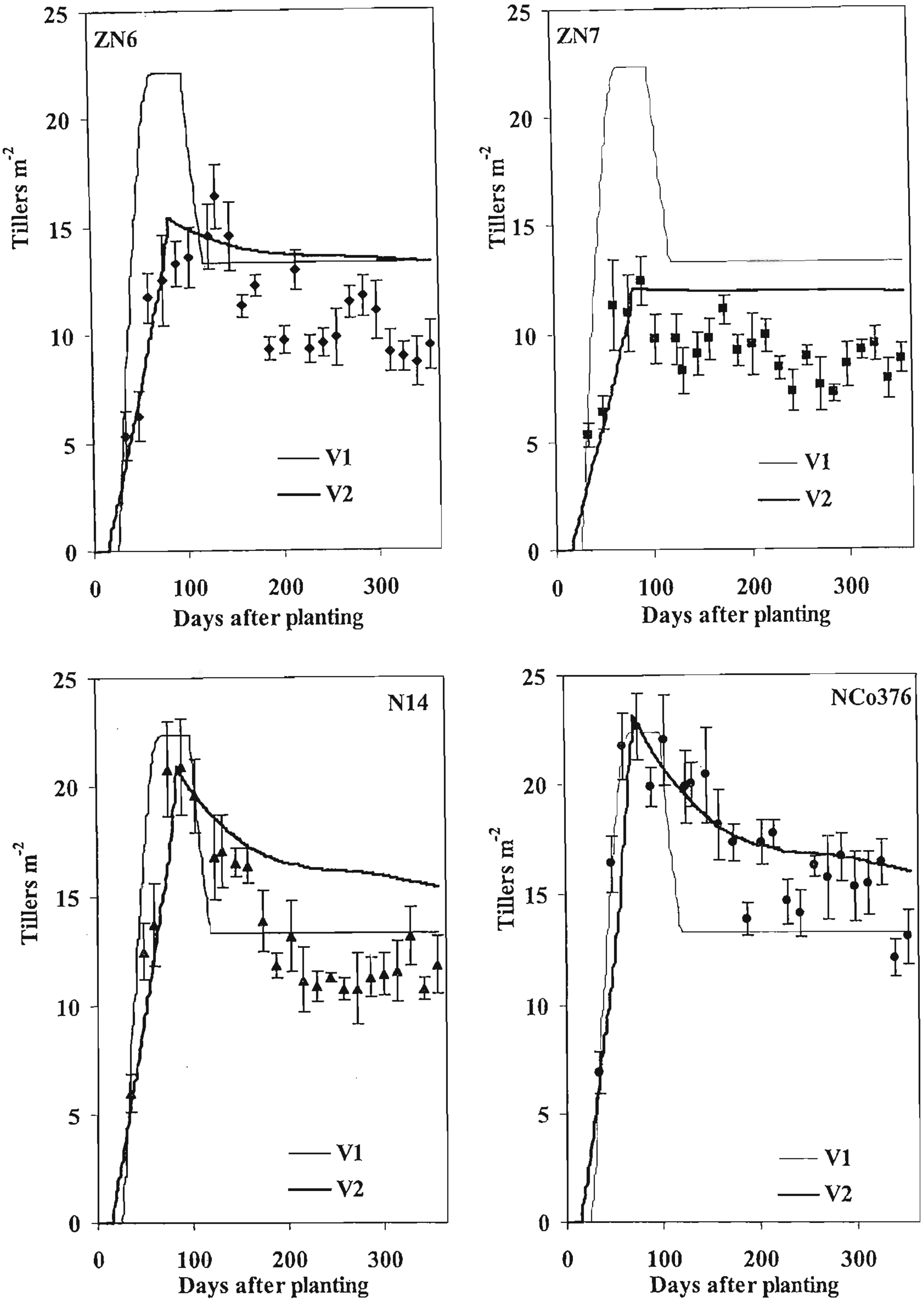

Fig. 6.3 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for tiller population (m^{-2}) of varieties ZN6, ZN7, N14 and NCo376

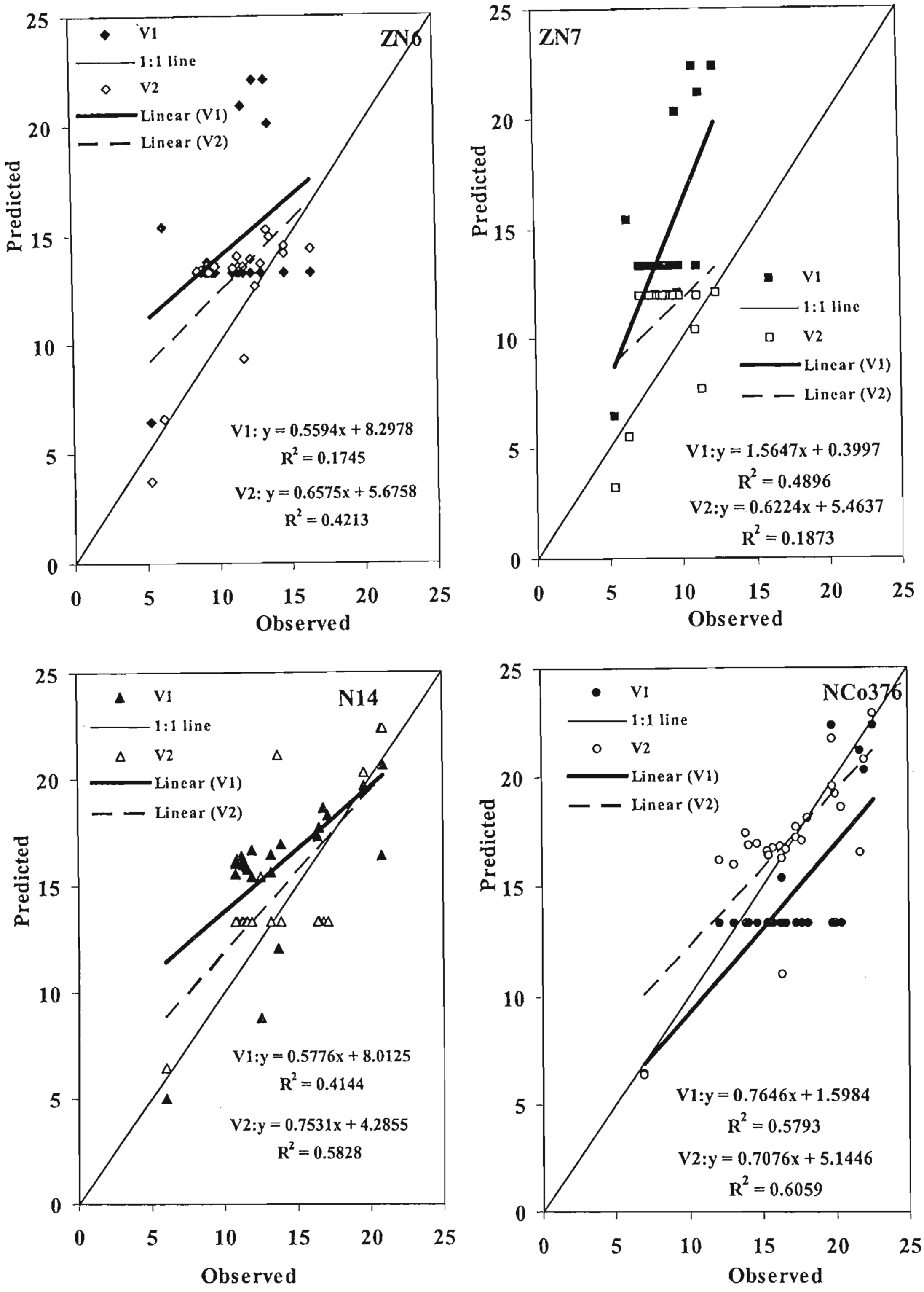

Fig. 6.4 Predicted versus observed tiller population (m^{-2}) of varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.4 Leaf area index

Generally, version 2 model predicted LAI better than version 1. The means of predicted and observed LAI were closer in version 2 than version 1 while the MAE, MRAE (except NCo376) and RMSE (except NCo376) were lower for version 2 than version 1 (Table 6.5). The D-index was higher in version 2 (except for NCo376) than in version 1. Except for NCo376, there were higher RMSEs than RMSEu in both version 1 and version 2 but the values were lower in version 2. Both models estimated closely the LAI up to peak but after the peak, both models overestimated (Figs 6.5 and 6.6). Both models did not account for the decline in LAI after the peak as the crop aged (Fig. 6.6). The slope, intercept and R^2 of the predicted versus observed scatter showed very little change between version 1 and version 2 particularly for varieties N14 and NCo376 (Fig. 6.5). The minimum and maximum LAI was closer in version 2 than version 1. The standard deviations were higher in version 1 predicted LAI than version 2 predicted LAI while the coefficient of variation was higher in version 2 predicted LAI than version 1 predicted LAI (Table 6.5).

Table 6.5 Evaluation of CANEGRO canopy models version 1 (V1) and version 2 (V2) in predicting the leaf area index of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	2,502		2,015		3,145		2,497	
Mean P	4,532	3,617	4,575	3,120	4,953	4,609	3,833	3,974
MAE	2,037	1,219	2,570	1,238	1,829	1,542	1,361	1,575
MRAE	0,834	0,511	1,284	0,672	0,635	0,517	0,769	0,792
RMSE	2,520	1,585	3,020	1,589	2,325	2,032	1,881	2,023
RMSEs	2,105	1,161	2,636	1,122	1,535	1,866	1,478	1,349
RMSEu	1,385	1,079	1,473	1,097	1,429	1,374	1,328	1,398
D-index	0,654	0,764	0,468	0,665	0,758	0,761	0,740	0,669
b	1,475	1,265	1,664	1,202	1,306	1,305	0,856	0,976
a	0,886	0,453	1,222	0,698	0,501	0,848	1,694	1,538
R^2	0,623	0,672	0,532	0,517	0,689	0,671	0,417	0,455
n	23	23	23	23	23	23	23	23
Maximum O	4,178		3,332		5,264		4,718	
Maximum P	6,730	5,310	6,630	4,440	7,360	6,720	5,380	5,480
Minimum O	0,064		0,062		0,082		0,084	
Minimum P	0,010	0,020	0,010	0,020	0,010	0,030	0,010	0,030
Std O	1,248		0,965		1,551		1,324	
Std P	2,305	1,926	2,202	1,614	2,473	2,441	1,756	1,915
C.V. % O	49,87		47,902		49,33		53,04	
C.V.% P	50,85	53,24	48,14	51,73	49,92	52,96	45,83	48,19

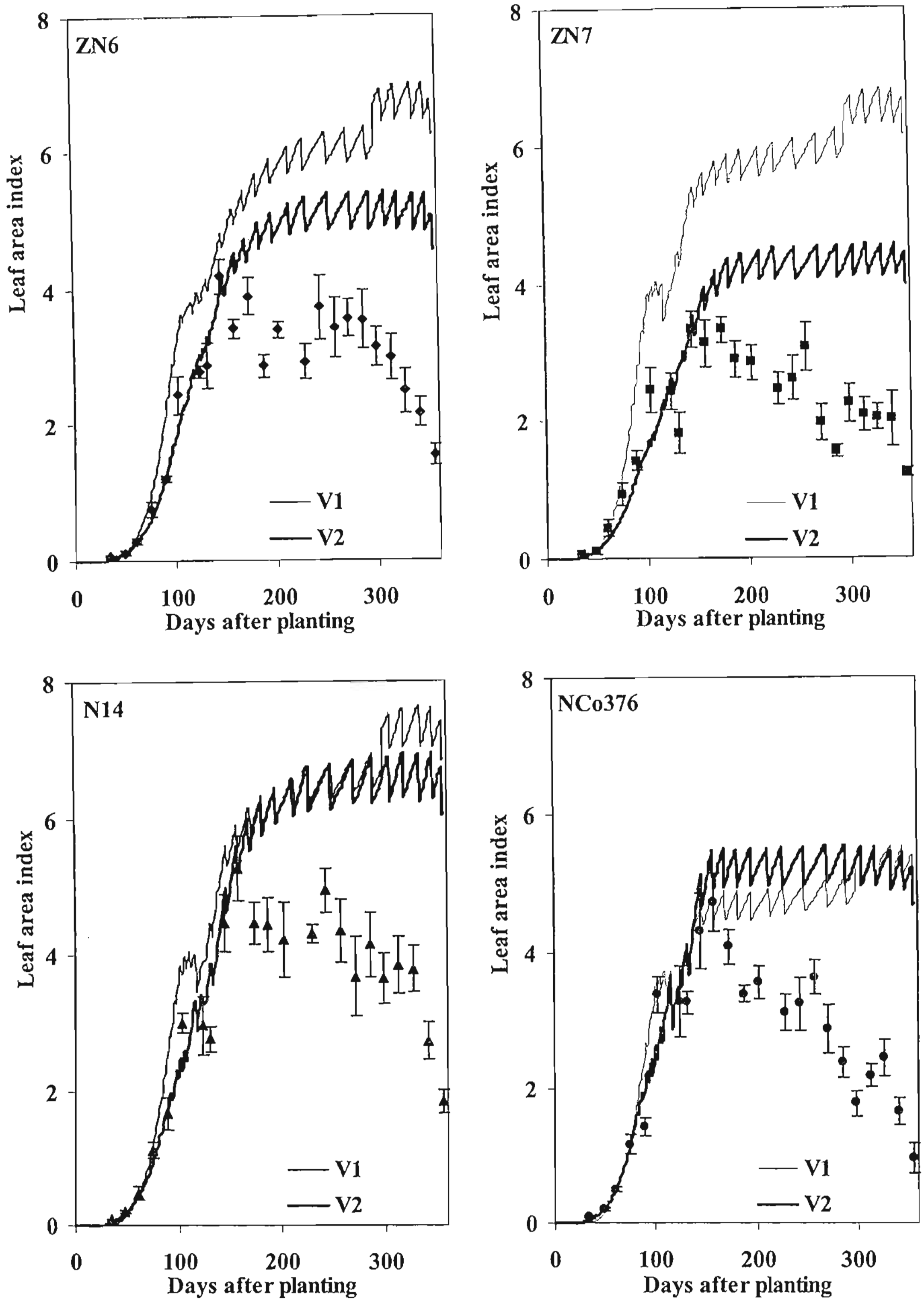

Fig. 6.5 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for leaf area index of varieties ZN6, ZN7, N14 and NCo376

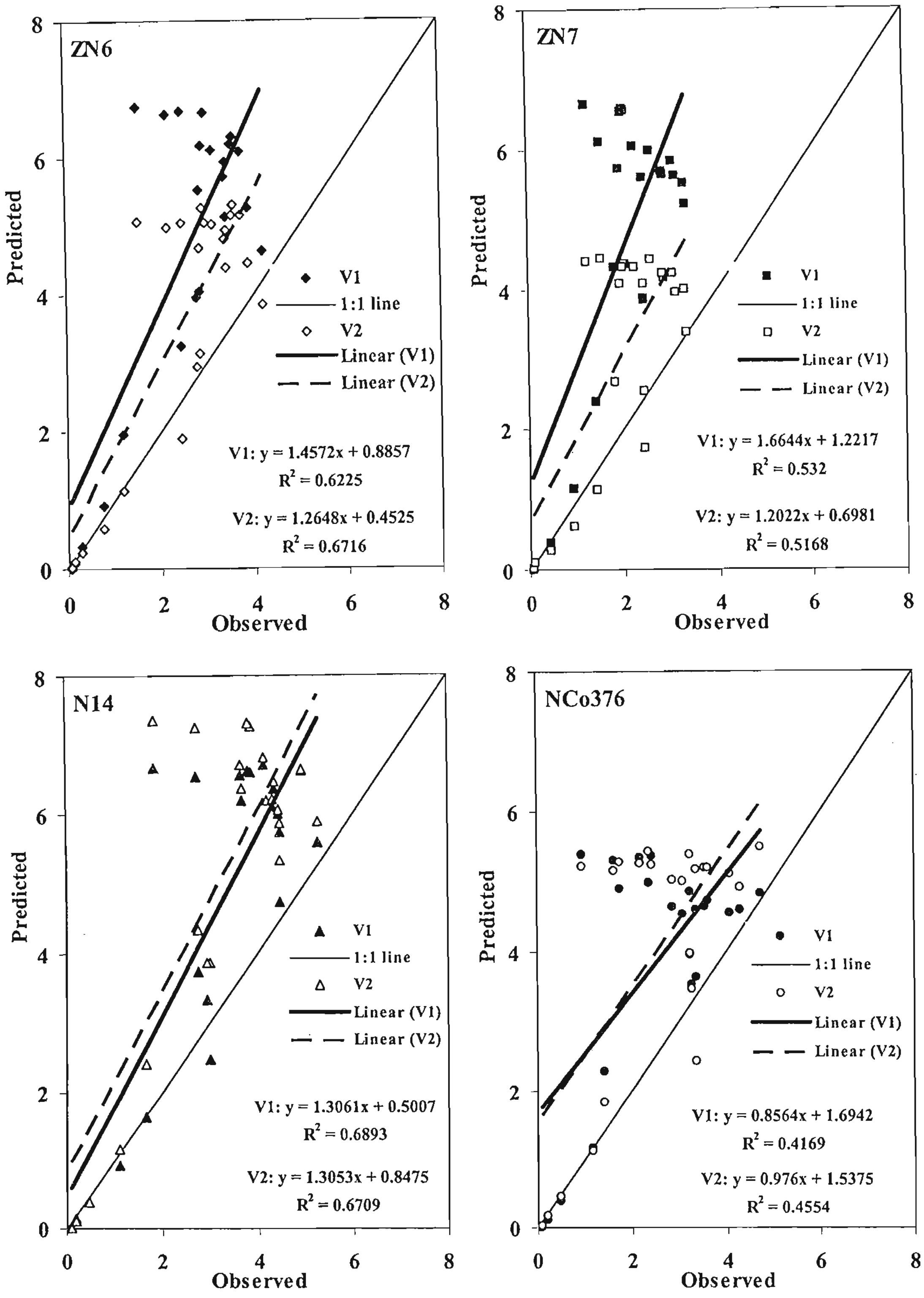

Fig. 6.6 Predicted versus observed leaf area index of varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.5 Green leaf numbers per stalk

Model evaluation statistics showed that the mean of observed and predicted green leaf numbers per stalk (except for NCo376) were closer with version 1 than version 2. The MAE, MRAE and RMSE were lower while the D-index was higher in version 2 for varieties ZN6, N14 and NCo376 (Table 6.6). RMSEs were less than RMSEu for all varieties in version 1 while in version 2 RMSEs were higher than RMSEu for varieties ZN6 and ZN7. The high systematic errors in varieties ZN6 and ZN7 were because version 2 underestimated the green leaf numbers per stalk (Figs 6.7 and 6.8). Both models did not account for the decline in green leaf numbers per stalk as the crop aged. The minimum, maximum and variation of observed and predicted green leaf numbers per stalk were different. The slope, intercept and R^2 decreased from version 1 to version 2 (Fig. 6.7).

Table 6.6 Evaluation of CANEGRO canopy models version 1 (V1) and version 2 (V2) in predicting the green leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	10,190		10,807		9,646		8,516	
Mean P	10,721	8,971	10,775	8,875	10,775	8,815	9,951	8,500
MAE	1,534	1,276	1,380	2,016	1,899	1,228	2,052	1,265
MRAE	0,179	0,132	0,157	0,186	0,226	0,131	0,268	0,161
RMSE	1,905	1,550	1,794	2,236	2,307	1,473	2,495	1,566
RMSEs	0,911	1,238	0,513	2,031	0,914	1,217	1,484	0,325
RMSEu	1,672	0,934	1,719	0,936	2,895	2,423	2,006	1,532
D-index	0,864	0,865	0,874	0,755	0,796	0,852	0,687	0,780
b	1,367	0,896	1,248	0,697	0,805	1,233	1,250	0,786
a	-3,213	-0,155	-2,715	1,348	1,055	1,123	-0,690	1,809
R^2	0,731	0,789	0,692	0,702	0,647	0,599	0,472	0,377
n	24	24	24	24	24	24	24	24
Maximum O	12,958		14,175		12,805		11,062	
Maximum P	13,00	10,44	13,00	10,18	13,00	10,45	12,00	10,03
Minimum O	5,257		5,176		5,022		5,166	
Minimum P	1,340	2,770	1,34	3,390	1,340	3,220	1,340	2,910
Std O	2,060		2,107		1,985		1,549	
Std P	3,294	2,076	3,163	2,107	3,163	1,988	2,819	1,983
C.V. % O	20,213		19,50		20,58		18,19	
C.V.% P	30,73	23,15	29,35	19,73	29,35	22,52	28,33	23,33

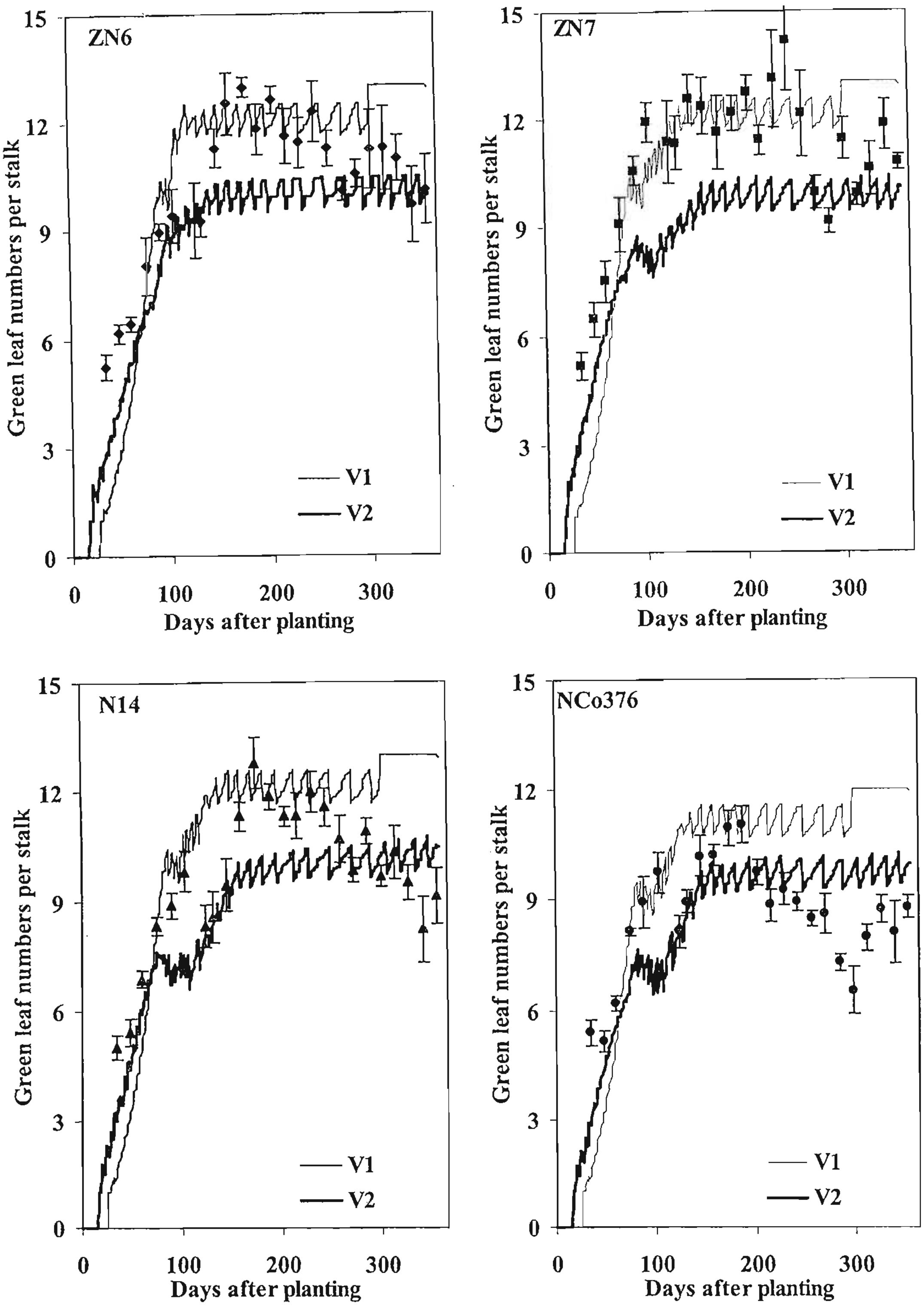

Fig. 6.7 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for green leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376

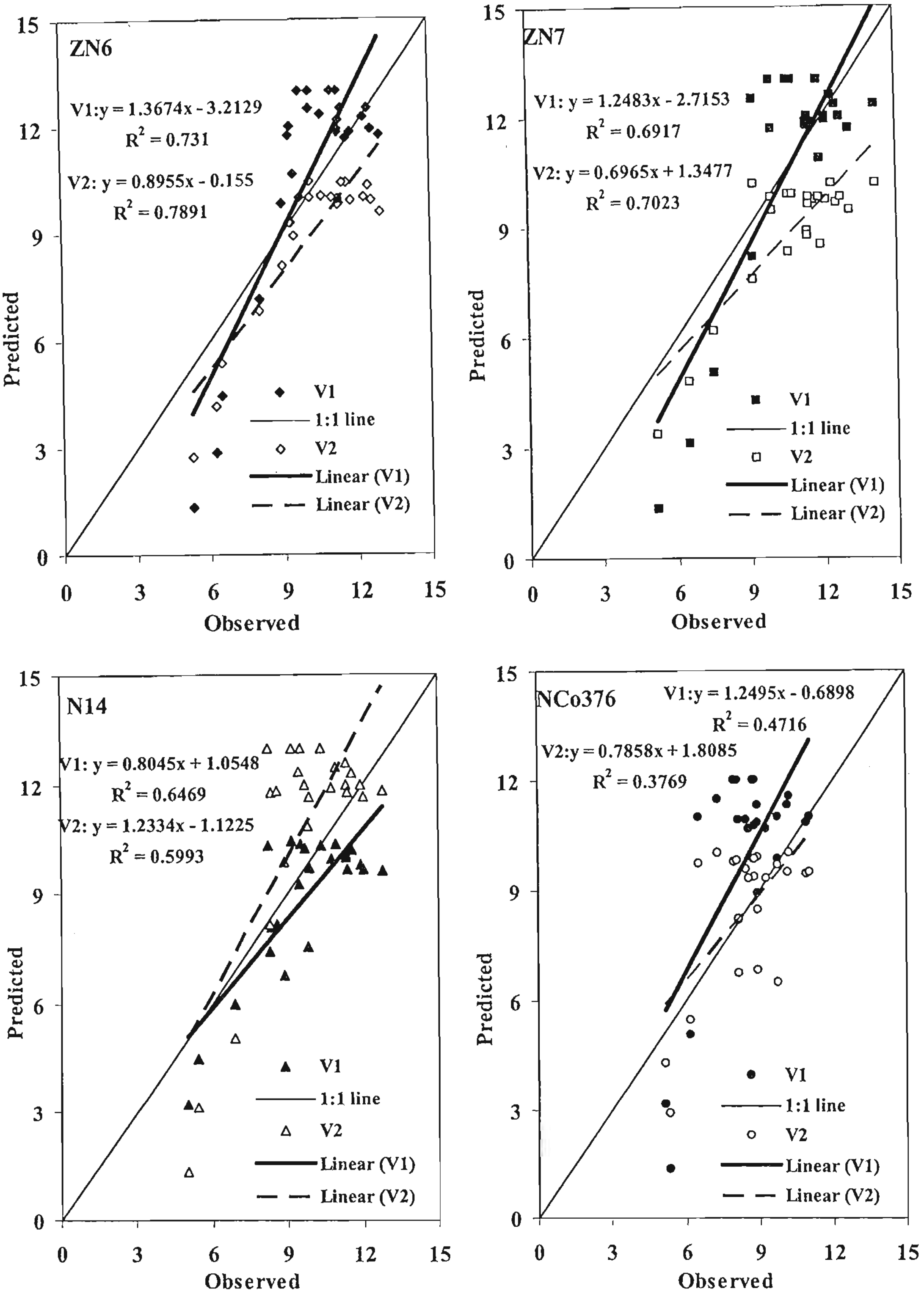

Fig. 6.8 Predicted versus observed green leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.6 Dead leaf numbers per stalk

The means of predicted dead leaf numbers per stalk for version 2 were higher than those of observed and version 1 (Table 6.7). The MAE, MRAE and RMSE were higher in version 2 than version 1 while the D-index was lower in version 2 than version 1. Varieties ZN6 and ZN6 had lower RMSEs than RMSEu while N14 and NCo376 had higher RMSEs than RMSEu in both models. Variety N14 predicted dead leaf numbers were very similar for both version 1 and version 2. The slope of the predicted versus observed scatter for varieties ZN6, ZN7 and NCo376 were higher for version 2 than version 1. The minimum, maximum and variation of predicted dead leaf number per stalk showed very little change between version 1 and version 2. The models generally overestimated the dead leaf numbers per stalk (Figs 6.9 and 6.10).

Table 6.7 Evaluation of CANEGRO canopy models version 1 (V1) and version 2 (V2) in predicting the dead leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	8,961		10,982		10,457		10,089	
Mean P	10,129	10,800	12,559	13,272	12,559	12,659	13,389	14,295
MAE	2,046	2,430	2,632	3,085	2,421	2,431	3,347	4,247
MRAE	0,475	0,545	0,559	0,584	0,542	0,555	0,817	1,213
RMSE	2,567	2,995	3,261	3,731	2,896	2,925	3,931	4,842
RMSEs	1,475	1,934	1,936	2,435	2,217	2,104	3,363	4,277
RMSEu	2,101	2,287	2,625	2,827	2,000	1,919	2,035	2,271
D-index	0,968	0,958	0,960	0,951	0,965	0,965	0,938	0,911
b	0,879	0,919	0,869	0,904	1,034	1,010	1,090	1,106
a	2,250	2,561	3,016	3,349	1,845	1,997	2,396	3,135
R^2	0,907	0,900	0,890	0,882	0,944	0,937	0,938	0,926
n	24	24	24	24	24	24	24	24
Maximum O	26,322		30,836		25,678		22,450	
Maximum P	21,00	21,97	24,00	24,97	24,00	24,95	25,00	25,98
Minimum O	0,070		0,141		0,079		0,084	
Minimum P	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Std O	7,614		8,754		7,726		7,417	
Std P	7,030	7,380	8,065	8,421	8,065	8,224	8,344	8,526
C.V. % O	84,97		79,72		73,89		73,51	
C.V.% P	69,41	68,34	64,22	63,45	64,21	64,97	62,32	59,64

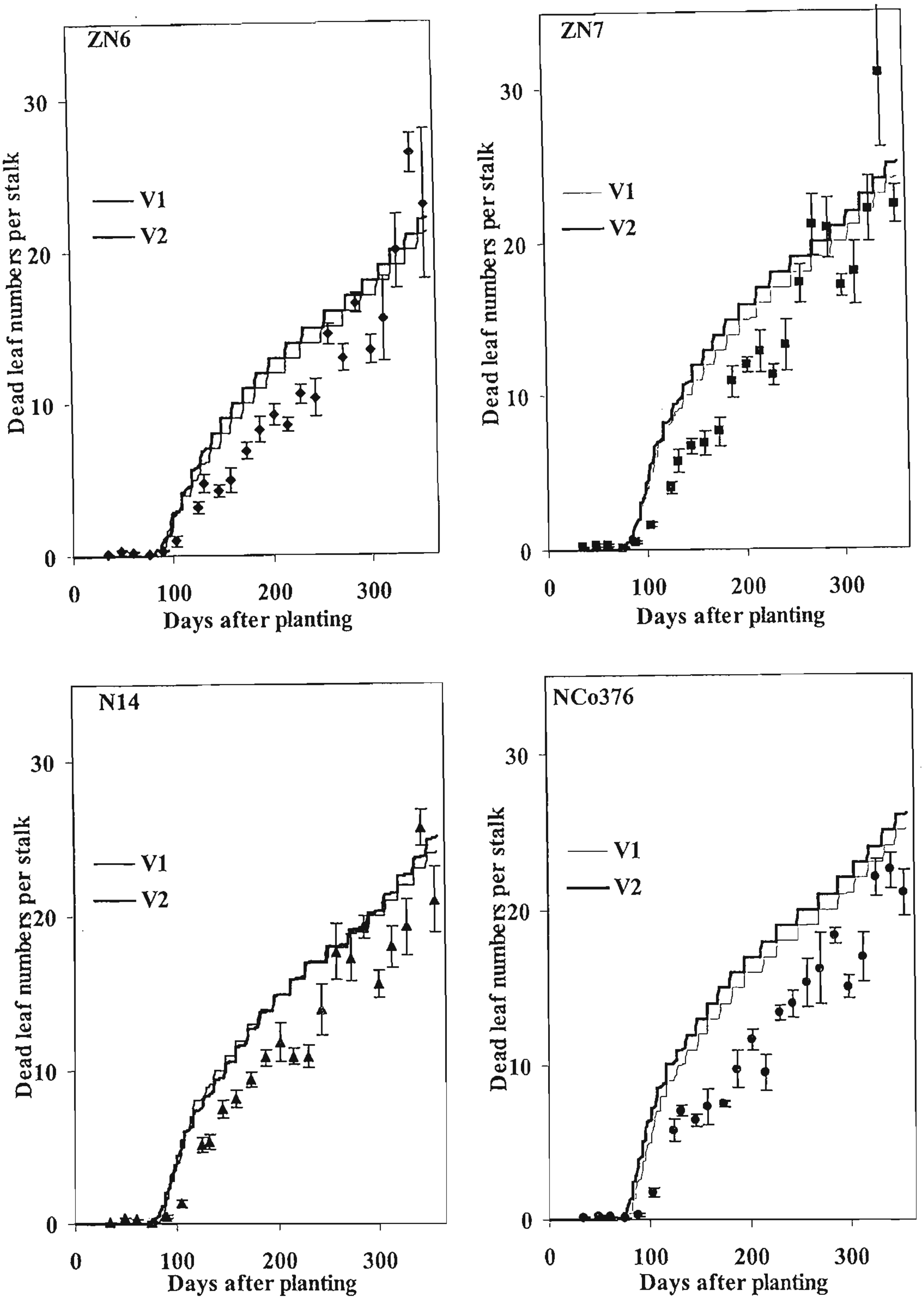

Fig. 6.9 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for dead leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376

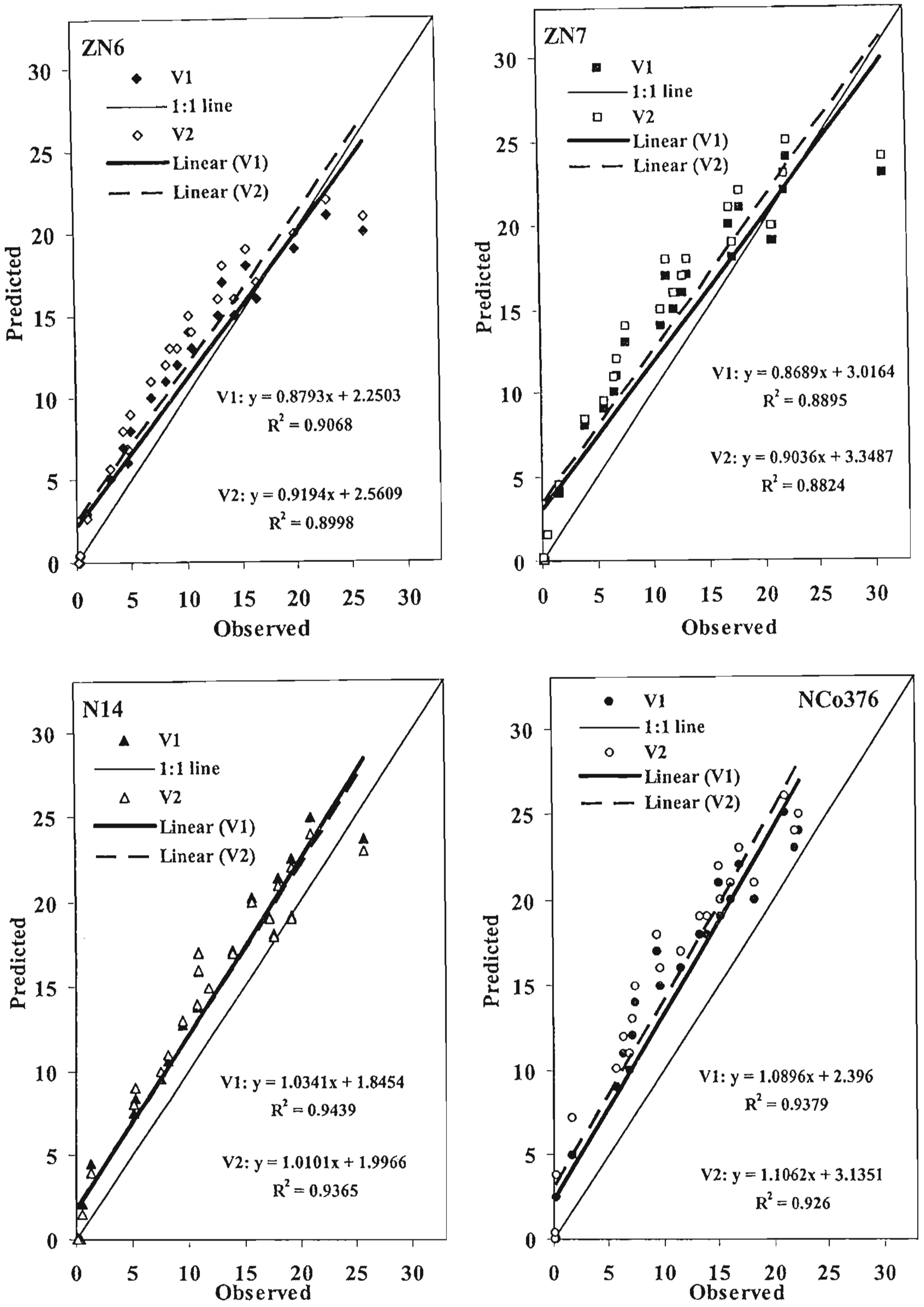

Fig. 6.10 Predicted versus observed dead leaf numbers per stalk of varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.7 PAR interception

The predicted means of intercepted PAR of version 2 model were closer to observed means than those of version 1 model. The MAE, MRAE and RMSE were lower in version 2 than version 1 while the D-index was higher in version 2 than version 1 (Table 6.8). The RMSEs was higher than RMSEu in both versions. Both models showed systematic overestimation of intercepted PAR (Figs 6.11 and 6.12). The slope, intercept and R^2 (except N14) were higher, lower and higher, respectively, in version 2 canopy model compared to version 1 model (Fig 6.11). The minimum predicted intercepted PAR was closer to observed values in version 2 than version 1 while the variation within data was closer between observed and predicted for version 2 canopy model than version 1.

Table 6.8 Evaluation of CANEGRO canopy models version 1 (V1) and version 2 (V2) in predicting the intercepted PAR (%) of varieties ZN6, ZN7, N14 and NCo376. O = observed data. P = predicted data

	ZN6		ZN7		N14		NCo376	
Parameters	V1	V2	V1	V2	V1	V2	V1	V2
Mean O	66,139		70,412		82,636		75,874	
Mean P	95,000	86,111	96,889	83,778	96,889	92.222	96,558	93,778
MAE	28,861	19,972	26,477	13,366	14,253	9,586	20,682	17,904
MRAE	0,506	0,335	0,406	0,194	0,180	0,118	0,295	0,254
RMSE	30,971	20,967	27,992	14,010	15,382	10,351	22,317	19,200
RMSEs	30,632	20,349	27,790	13,368	9,623	15,065	22,037	18,827
RMSEu	4,563	5,047	3,361	4,200	6,915	7,261	3,506	3,778
D-index	0,463	0,668	0,401	0,750	0,489	0,725	0,454	0,525
b	0,362	0,758	0,282	1,007	0,902	0,422	0,349	0,503
a	71,030	36,009	77,012	12,868	17,719	62,042	70,103	55,631
R^2	0,621	0,854	0,494	0,888	0,799	0,567	0,575	0,708
n	9	9	9	9	9	9	9	9
Maximum O	93,78		92,48		95,60		96,52	
Maximum P	99	99	99	99	99	99	99	99
Minimum O	39,52		50,22		67,42		53,72	
Minimum P	76	59	84	59	84	74	82	79
Std O	17,083		12,476		8,947		12,403	
Std P	7,858	14,004	5,011	13,330	5,011	9,025	5,703	7,412
C.V. % O	25,83		17,718		10,83		16,347	
C.V.% P	8,27	16,26	5,172	15,911	5,17	9,79	5,907	7,904

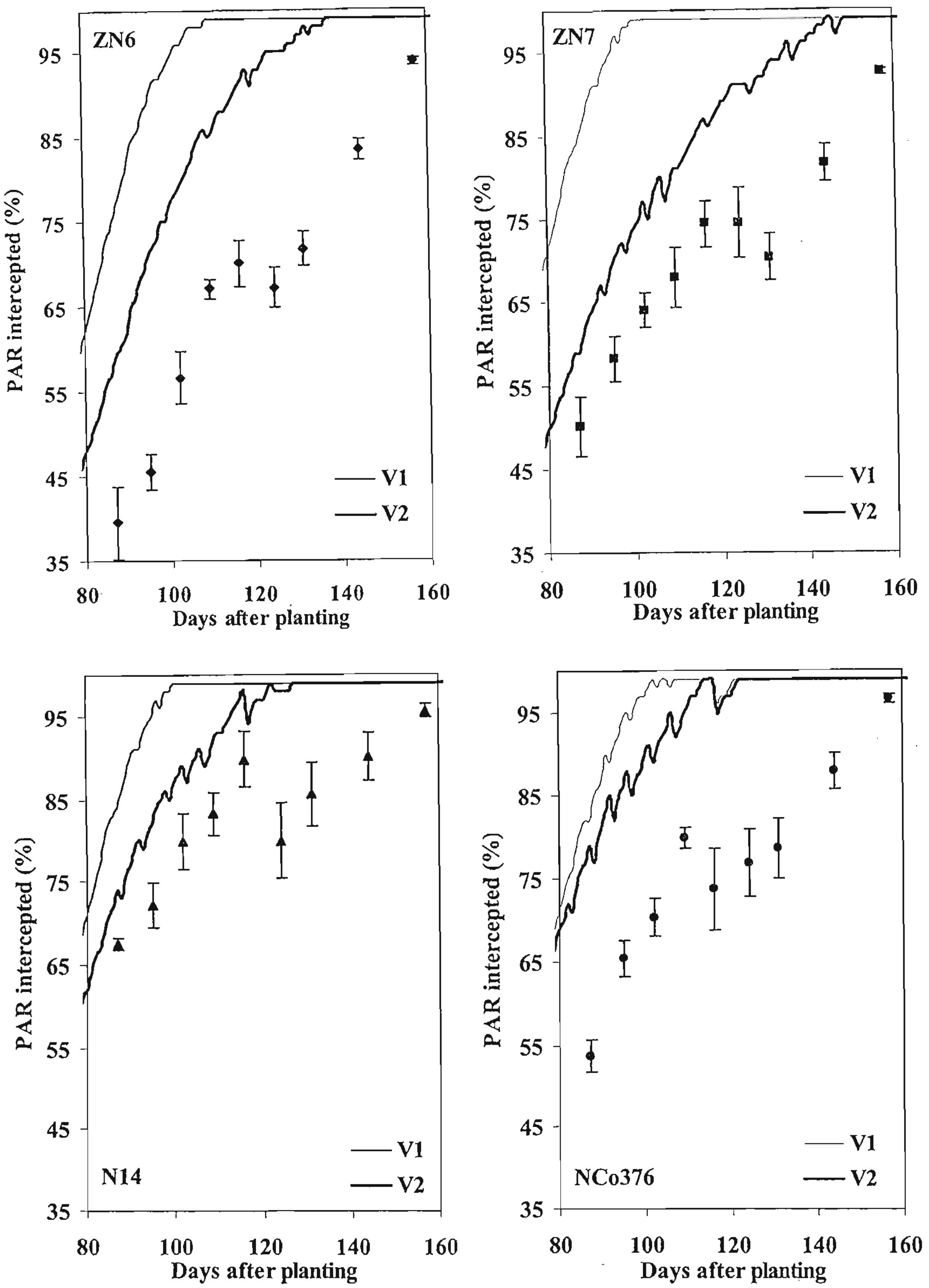

Fig. 6.11 Time series graph for predicted data (solid lines) generated using CANEGRO canopy models version 1 (V1) and version 2 (V2) and measured data (points with error bars) for intercepted PAR (%) for varieties ZN6, ZN7, N14 and NCo376

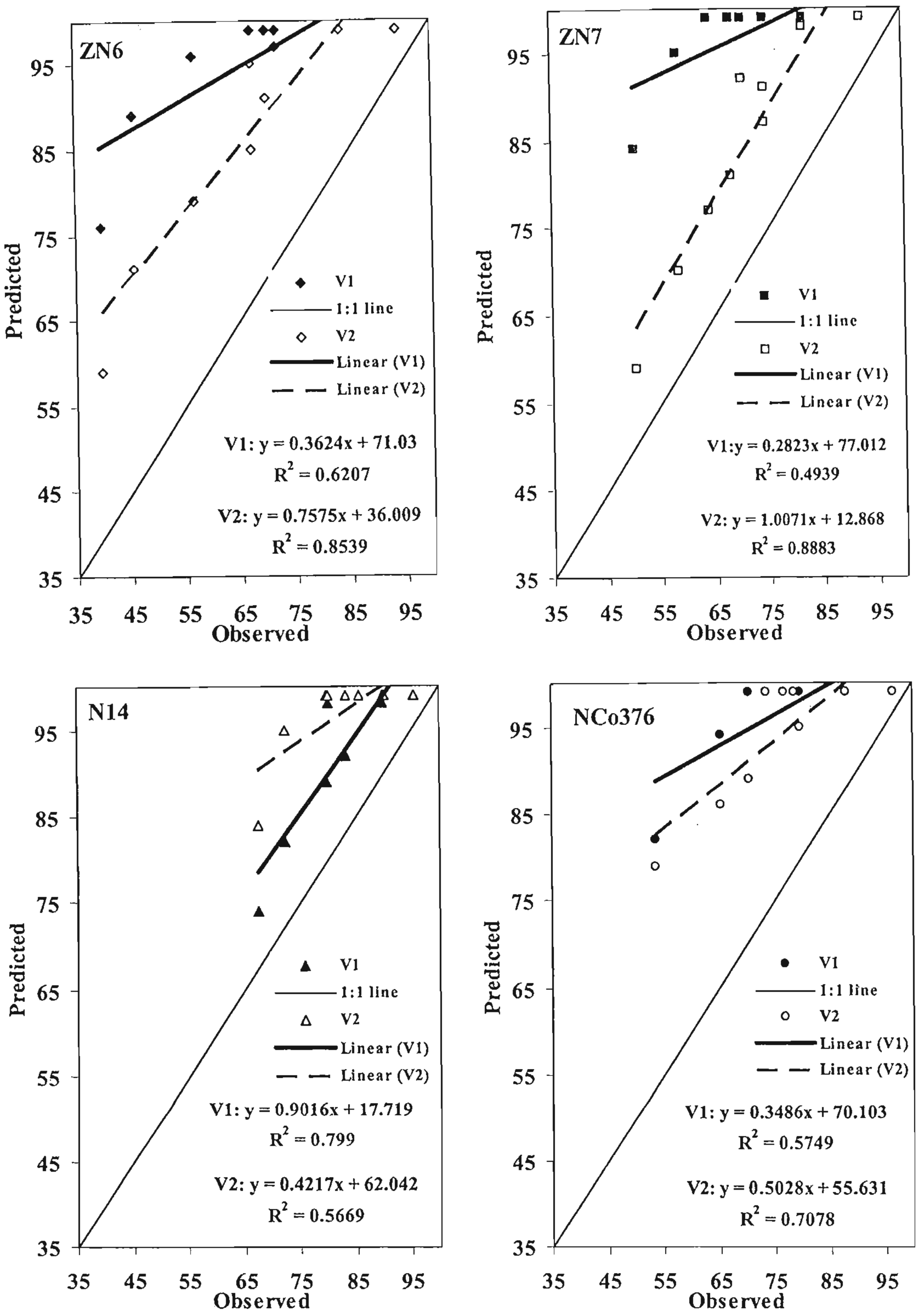

Fig. 6.12 Predicted versus observed intercepted PAR (%) for varieties ZN6, ZN7, N14 and NCo376. CANEGRO canopy models version 1 (V1) and version 2 (V2) were used to generate the predicted data

6.4.8 Discussion

The statistics showed a close relationship between observed and predicted tiller heights. The scatter and time series graphs showed that both version 1 and version 2 models overestimated tiller heights in the early stages of growth and underestimated thereafter. The broken stick approach could improve the modelling of tiller height development (Section 4.3.3) as it separates the stalk development into phases possibly controlled by different crop and environmental factors and thus improve the timing of these phases.

The statistics showed that version 2 was better than version 1 in predicting tiller population. Version 2 performed best in estimating the tiller development of NCo376 while it overestimated the stable tiller population of ZN6 and ZN7 and underestimated the tiller senescence of N14. A broken stick model (Sections 4.3.1 and 4.3.2) could improve the modelling of tiller population development as it separates the developmental stages and could possibly improve the timing of the developmental phases.

Both models overestimated LAI from peak and thereafter. The statistics showed that version 2 was better than version 1 particularly for varieties ZN6 and ZN7. The failure by the models to account for the decrease in LAI in older crops could be due to its failure to account for the decrease in green leaf numbers per plant towards end of crops cycle (Fig. 4.9) and the decrease in individual leaf area in leaves at the top of stalks as the crops ages (Fig. 5.5).

The statistics showed that version 2 was poorer than version 1 in predicting the green leaf numbers per stalk for varieties ZN6, ZN7 and N14 as it underestimated green leaf numbers per stalk. The models failed to predict the decrease in green leaf numbers with crop age.

Both models overestimated dead leaf numbers per stalk with version 1 being closer to the observed than version 2. The use of the broken stick model could improve the modelling of dead leaf numbers per plant (Fig. 4.8).

Both models overestimated intercepted PAR with version 2 model providing better estimates than version 1. The models achieved peak intercepted PAR too early and maintained peak up to harvest and thus failed to predict the decrease in intercepted PAR by end of crop cycle which is caused by a decrease in LAI. The PAR measurements used were measured at mid-day only.

Generally, version 2 canopy model performed better than version 1 in modelling variety differences in canopy growth and development. More refinements are required to improve version 2 model particularly for LAI where it overestimated LAI after the peak and did not account for the decline in LAI with increasing crop age. There is a need to validate the models with an independent data set.

Chapter 7: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 General discussion

The major weakness of the CANEGRO model was modelling variety differences in canopy growth and development. This was because there were no descriptions of variety canopy development parameters in the CANEGRO model. This study aimed to identify possible variety canopy development parameters that could be included in the model descriptions. The canopy development parameters that would describe the variety differences in the development of tillers and leaves would improve the modelling of variety differences in canopy growth and development. The model was designed to predict the canopy growth and development of NCo376 only.

The literature has shown the importance in developing canopy growth and development parameters for different varieties. The ability to model variety differences in canopy growth and development could be used in developing breeding strategies for varieties suited to specific growing conditions (Butterfield and Nuss, 2002). Assessment of variety traits that would be more stable and adaptable can be done with such models. Plant ideotypes can be assessed using models and these can then be tested in the field. Growers in deciding the varieties that are likely to yield best under different growing conditions could also use models, which can model variety differences. Variety choice is critical in increasing sucrose production (Zhou, 2001; Redshaw and Donaldson, 2002).

The phases of development of green leaf population and tiller population followed a similar pattern but there were variety differences in the period required to complete these phases. Leaf emergence and tillering rates differed among varieties. Thermal time was the major driver of tillering and leaf emergence in all varieties while the other factors including thermal time could be driving the senescence phases. The development of tiller and leaf populations could be described using a broken stick model with two linear equations. The tillering and leaf increase could be described by the first equation while the tiller and leaf senescence phases could be described by the second equation. The use of polynomial equations in modelling tiller population development (Inman-Bamber, 1991a, 1994b) assumed that tillering and tiller senescence were driven by thermal time but this study showed that tillering was driven by thermal time and tiller senescence by PAR transmission to the bottom of the canopy. The potential of the broken stick model in improving the modelling of tiller and leaf population development needs further investigation.

The numbers of dead leaves started increasing around the peak leaf population and showed a linear increase thereafter. Very few dead leaves were observed before peak tiller population. This may mean that a threshold leaf area per tiller could be required before leaf senescence occurs. The effect of PAR transmission to bottom leaves could be triggering leaf senescence. Both hypotheses may need to be investigated in future work.

The three phases of tiller development were initiation of stalks, rapid stalk elongation and sucrose accumulation. The initiation of stalks was exponential, while the rapid stalk elongation and sucrose accumulation were linear. Stalk elongation decreased during sucrose accumulation phase. A broken stick with an exponential first stage and two linear stages could be used to describe tiller height growth and development.

The data showed that peak leaf and tiller population, start of stalk elongation, start of tiller and leaf senescence appeared to occur at the same time and there were variety differences. These aspects of canopy development need further investigation because if the leaf and tiller population and stalk elongation development for a variety coincide, the measurement of one could be used to predict the others. This coincidence could have importance to breeders during the selection process as some kind of a marker.

The base temperatures showed that internode formation occurred at lower temperatures than tillering and stalk elongation, while the canopy height development required higher temperatures. Tillering and stalk elongation occurred at similar base temperatures. The varieties had different base temperatures for internode formation, tillering, stalk elongation and canopy height development. The data also showed that there is a possibility of grouping varieties with similar base temperatures for certain developmental processes and this aspect may need further investigation.

The physiological parameters for canopy development showed that the notable variety differences in canopy development were that N14 had the highest rate of shoot emergence and ZN6 had lowest rate; ZN7 had the highest rate of leaf appearance; N14 had the largest and NCo376 the smallest leaves; tiller senescence commenced the earliest in ZN7 and the latest in ZN6; tiller population was the highest in NCo376 and lowest in ZN7 and there were variety differences in proportion of millable stalks to peak tiller population. This implied that ZN7 produced relatively large leaves at a faster rate compared to other varieties. ZN7 produced few tillers and tiller senescence started earlier than NCo376, a high tillering variety.

Variety N14, had the highest LAI after canopy cover or LAI of 3 and intercepted the highest proportion of incident PAR. As biomass production is dependant on the amount of PAR intercepted (Singels and Donaldson, 2000), N14 is likely to produce more biomass than the other varieties. Varieties N14 and NCo376 intercepted more PAR than ZN6 and ZN7. The difference between these varieties is that N14 and NCo376 are high population while ZN6 and ZN7 are low population. Variety N14 had large leaves but NCo376 had small leaves and this could mean that leaf size is less important for PAR capture. Varieties ZN6, N14 and NCo376 had similar leaf angles and ELADP values, but they intercepted PAR differently, and therefore canopy architecture could be less important in PAR interception. Therefore the role of leaf size and canopy architecture does not seem that important in PAR capture and tiller population could be the most important factor determining PAR interception and possibly biomass production. This could mean that selecting for high tillering in breeding programmes could be the key to achieving high cane yields. High density planting aimed at increasing tiller population could also hold as the key to increasing yield. Work done in Australia by Bull and Bull, (1996 and 2000) and Bull and Mcleod (2000) has shown there could be potential of increasing yields using high density planting. Research needs to explore these potentials. The effect of high density planting on the ratio of millable stalks to peak tiller population may need further investigation.

The modelling of leaf emergence in CANEGRO is based on the broken stick equations. This study has shown the weaknesses of the broken stick equations, which assume that the rate of leaf emergence is constant over a wide range of leaves along the stalk, from 1 to 14 and 14 to 30 (Inman-Bamber, 1991a, 1994b). However, the data in this study showed that there is a wide variation and therefore the gradual increase in phyllochron intervals offers a better and probably more accurate method of modelling leaf development and particularly the variety differences. The data also showed a linear increase in thermal time required for each successive leaf to emerge on the stalk (^{0}C day/leaf) or the phyllochron gradient. There were variety differences in the phyllochron gradient. The phyllochron gradient can be used as a variety parameter for modelling leaf emergence in sugarcane. More work, is however, required to quantify whether the phyllochron gradient is stable over seasons and ratoons.

The model evaluation statistics showed that version 2 canopy model was generally better than version 1. However, both models were in most cases not following the development phases. The scatter plots and time series graphs showed that both version 1 and version 2 overestimated tiller heights in the early phases of crop growth and underestimated later. Version 2 performed best in estimating the tiller population development of NCo376 while it overestimated the stable tiller population of ZN6 and ZN7 and also underestimated the tiller senescence of N14. The broken stick approach could improve the modelling of tiller heights and tiller population development. This approach separates the developmental phases as these are possibly affected by different crop and environmental factors and may improve the timing of the developmental phases. Both models overestimated LAI from the peak and thereafter and the models failed to account for the decline in LAI in older crops. The statistics showed that version 2 was poorer than version 1 in predicting the green leaf numbers per stalk for varieties ZN6, ZN7 and N14. Version 2 underestimated green leaf numbers per stalk for varieties ZN6, ZN7 and N14. Both models did not account for the decrease in green leaf numbers per stalk with crop age. The decrease in green leaf numbers per stalk and decrease in individual leaf area at the top of the stalk (Fig. 5.5) could be the cause for the decrease in LAI. Both models overestimated dead leaf numbers per stalk. The use of the broken stick approach could improve the modelling of dead leaf numbers per stalk. Version 2 provided better estimates of intercepted PAR than version 1. Both models achieved peak intercepted PAR too early and maintained peak up to harvest. This does not account for the decrease in intercepted PAR by the end of the crop cycle due to the decrease in green leaves per stalk and the decrease in LAI. Therefore the overestimation of LAI could be causing the overestimation of intercepted PAR. The use of green leaf population development (Fig. 4.5) and leaf area of individual leaves (Fig. 5.5) may improve the prediction of LAI by the canopy models.

7.2 Conclusions

From the literature we can conclude that the major weaknesses of most crop models including CANEGRO is modelling variety differences in canopy growth and development. The inability of crop models to predict variety differences has limited their use in plant breeding. Despite this weakness, the potential use of a CANEGRO version that can predict variety differences in canopy growth and development include variety choice, analyzing plant ideotypes suitable for specific environments and developing future breeding and selection strategies.

There are variety differences in leaf and stalk population development. Thermal time is the main driver of tillering and leaf emergence. However thermal time plays a less important role in tiller and leaf senescence. The data showed that tiller senescence and leaf senescence could be triggered by reduced transmitted PAR and that other factors such as moisture stress could be involved in driving the senescence phases.

There were significant (P = 0,01) variety differences in peak and final tiller populations. The ratio between final and peak tiller population showed variety differences. This could be a potential parameter for predicting final tiller population. Varieties with a higher ratio are likely to be more desirable as they convert most of their tillers to millable stalks.

The study showed that leaf senescence or death occurred from peak tiller population and increased linearly thereafter. There were variety differences in dead leaf population.

A broken stick approach to modelling tiller and leaf population development appears to offer a better alternative to polynomial equations particularly considering that the environmental factors driving tillering and leaf emergence, and tiller and leaf senescence are different. Therefore a single polynomial equation cannot adequately explain the two processes affected by different environmental factors.

There were variety differences in tiller growth and development. The three stages of sugarcane tiller growth and development identified were stalk initiation, rapid stalk elongation and sucrose accumulation. The data showed that stalk elongation slowed during sucrose accumulation but internode formation continued although the internodes were shorter due to slower stalk elongation.

The coinciding of peaks (tiller and leaf populations), start of rapid stalk elongation, tiller and leaf senescence could be indicating links between parameters. These links offers a potential to develop markers for these characters useful to plant breeders.

This study showed that there were variety differences in base temperatures for tillering; stalk elongation, internode formation and canopy height growth. The data showed that internode formation occurred at a lower base temperature than tillering and stalk elongation while canopy height development required higher base temperatures than tillering and stalk elongation.

There were variety differences in thermal time to shoot emergence and 16 °C appeared to be the most likely base temperature for shoot emergence. There were significant variety differences ($P = 0{,}01$) in the numbers of eyes that emerged after planting. High stalk population varieties had higher percent emergence than low stalk population varieties.

The varieties had different phyllochron intervals. The gradual phyllochron intervals could offer a better method of predicting leaf emergence than the broken stick equations. There were variety differences in phyllochron gradients and this could be a possible variety parameter for modelling leaf emergence.

There were significant differences between varieties in the area of the youngest biggest leaf and N14 produced the largest and NCo376 the smallest leaves. The LAI between varieties was significant after canopy closure or LAI of 3.

There were significant differences in PAR interception by varieties with N14 intercepting the highest percentage of incident PAR. The trends in PAR interception were similar to those of LAI development. Therefore LAI is important for PAR interception.

There were no significant differences in extinction coefficients but N14 had the lowest value while ZN7 had the highest. The R^2 values of the relationship between LAI and ln(transmitted PAR) were higher when LAI was measured with a SunScan Ceptometer than when measured with a Delta-T leaf area meter. Therefore we can conclude that extinction coefficients could be better determined using SunScan measured LAI values.

There were significant differences (P = 0,05) in leaf angles and ELADP values between varieties. The leaf angles appeared to be important in PAR interception and high leaf angles in variety ZN7 resulted in lower PAR transmission.

The model evaluation showed that CANEGRO canopy model version 2 was better than version 1. The version 2 model predicted tiller heights and dead leaf numbers per stalk well, was moderate for intercepted PAR, tiller population and green leaf numbers per stalk and poor at predicting LAI. It appears the model could not account for the general decrease in green leaf numbers per stalk and the decrease in LAI in older crops. The study concluded that the overestimation of intercepted PAR by the models could be caused by the overestimation of LAI as LAI is used in determining intercepted PAR in the models. Both models were generally not in phase with the sigmoid pattern of tiller height development.

7.3 Recommendations and suggestions for further research

This study managed to shed some light on the important aspects of modelling variety differences in canopy growth and development of sugarcane under irrigated conditions. However, the study also revealed some areas where information gaps exist and future research would help fill these gaps and thus improve the understanding and requirements for modelling canopy growth and development of sugarcane.

Peak tiller and leaf population, start of tiller and leaf senescence and start of stalk elongation appear to coincide. Therefore one parameter could be used to describe this development stage. There is a need to identify which traits would best describe the development stage and only determine that as the variety parameter for use in CANEGRO. The trait that is easiest to measure is likely to be the most desirable.

The proposed broken stick approach to modelling tiller and leaf population development needs further investigation for seasonal and ratoon effects. The seasonal and ratoon effect on tillering and stalk elongation rates needs further investigation with regards to variety differences and whether there is need for seasonal parameters.

The major driver for the tillering and leaf emergence processes is thermal time but the major driver for the tiller and leaf senescence processes needs to be further investigated. The investigation may need to verify whether the senescence process is driven by environmental or physiological factors or a combination. If it is a combination, the most influential factors may need to be identified. A possible environmental factor could be PAR transmission while a possible physiological factor could be leaf area per tiller.

There may be a need to investigate further the base temperatures with early and mid season planted sugarcane. This study was based on a late-planted crop. There is need to group development stages with similar base temperatures and also group varieties with development stages that require similar base temperatures. This would help in modelling variety differences and in selecting potential varieties for different seasons and growing areas with different temperatures.

The trigger for stalk initiation is another area that requires further investigation. There is a need to investigate whether the trigger is environmental (possibly thermal time, PAR interception) or physiological (possibly threshold leaf area per tiller) or a combination.

There is need to investigate the stability of the phyllochron gradient as a physiological parameter and study the seasonal and ratoon effects on the phyllochron gradient. The causes of the sudden decrease in phyllochron intervals at the end of the crop cycle may need to be investigated. This phenomenon is undesirable as it could result in the sucrose in the stalks being reallocated to leaf emergence and thus lowering the sucrose content of stalks.

The tolerance of varieties to low PAR transmission needs further research. There is a need to verify if this is genetic or not. If it happens to be genetic, there is then a need to group varieties with similar tolerance to low PAR transmission and possibly further investigate if tolerant low stalk population varieties can increase their stalk population and cane yield with high density planting.

The final to peak tiller population ratio need further investigation as a variety parameter. Seasonal and ratoon effects on the ratio of final to peak tiller population for different varieties needs further research. There is a need to investigate how this ratio is affected by changing row spacing. The effect of variety tolerance to low PAR transmission at the start of tiller senescence on the ratio of final to peak tiller population may need to be investigated.

The thermal time per tiller needs further investigation for seasonal and ratoon effects. Further research is required to also investigate variation in thermal time per tiller from emergence to peak tiller population to identify if thermal time per tiller is constant from emergence to peak tiller population. This research would improve the modelling of tiller production and also help design management practices that would promote rapid tillering to improve final stalk population and possibly cane yield. This aspect could aid breeders as they can target selection during the peak tillering period to identify high tillering varieties.

The seasonal and ratoon effect on extinction coefficient needs further investigation. There is a need for investigating varieties with similar extinction coefficients. There is great need to investigate the best and cost effective method of determining extinction coefficients. This study showed that the SunScan ceptometer could possibly be more cost effective and accurate. The use of the SunScan to assess a wide range of varieties needs to be investigated further to identify appropriate methodologies that would improve accuracy.

The parameters defined in this study need to be measured for more varieties, in more environments over seasons and ratoons. Categorisation of varieties into groups with similar parameters is required. There is then a need to identify easily recognizable morphological and physiological attributes for each category. This type of research could be useful to sugarcane breeders in modelling variety differences and assessing characteristics likely to improve yield. It could also offer a potential way of identifying and assessing genetic markers for use in plant breeding.

There will be a need to examine the use of the broken stick approach in modelling tiller heights, tiller population and dead leaf numbers per stalk. The crop and environmental factors that affect the different development phases are different and modelling the phases separately could improve the predictions. Future work may need to focus on making the model in phase with the sigmoid pattern of tiller height development. There will be need to examine the causes of the models overestimating LAI. Possible causes could be a failure to account for the decrease in LAI with crop age caused by the decrease in green leaf numbers per stalk and the decrease in individual leaf area of leaves at the top of the stalk. There will also be a need to examine how much the improvement in prediction of LAI improves the prediction of intercepted PAR as the models use LAI to determine intercepted PAR.

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APPENDICES

Appendix 1: Weather data

Table A1.1 The minimum and maximum air temperature (°C), relative humidity (%) at 08h00 and 14h00, wind speed (m s^{-1}), A-pan evaporation (mm per day) and rainfall (mm per day) recorded at ZSAES weather station. The data are means of records collected from 1970-2001 (ZSAES long term weather data files)

Month	Tmin °C	Tmax °C	RH 08h00 %	RH 14h00 %	Wind speed m s^{-1}	Eto Mm/day	Rainfall mm/month
January	20,9	32,0	78,1	53,1	1,39	6,9	114
February	20,6	31,1	82,2	56,9	1,27	6,0	138
March	19,4	30,8	82,2	53,2	1,11	5,7	66
April	16,4	29,4	81,6	48,4	0,91	4,6	27
May	12,5	27,4	80,1	44,0	0,80	3,8	12
June	9,4	25,3	79,4	42,1	0,80	3,3	6
July	9,2	24,9	79,4	41,5	0,88	3,5	7
August	11,1	27,2	74,9	37,1	1,17	4,6	5
September	14,9	29,9	70,8	38,1	1,57	6,1	13
October	17,6	31,1	69,2	40,9	1,85	7,1	27
November	19,5	32,1	70,5	46,2	1,67	7,2	76
December	20,4	32,0	74,2	50,8	1,51	7,1	102

Table A1.2 The minimum and maximum air temperature (°C), relative humidity (%) at 08h00 and 14h00, wind peed (m s^{-1}), A-pan evaporation (mm per day) and rainfall (mm per day) recorded at ZSAES weather station. The data are monthly means of records collected during the experimental period (October 2001 to October 2002)

Month	Tmin °C	Tmax °C	RH 08h00 %	RH 14h00 %	Wind speed m s^{-1}	Eto mm/day	Rainfall mm/month
October	17,8	32,1	70,8	38,8	1,79	7,2	6,6
November	20,9	31,7	78,6	54,9	1,55	6,0	68,1
December	21,0	30,6	82,9	66,0	1,27	4,8	142,2
January	20,3	33,2	77,2	44,7	1,48	8,2	29,7
February	19,1	33.6	72,5	43,7	1,37	7,3	3,7
March	19,7	32,6	77,5	42,4	1,37	6,8	6,7
April	16,7	30,0	82,6	47,8	1,03	4,6	22,5
May	12,8	28,6	72,6	39,7	0,92	4,0	0,0
June	10,2	24,7	72,6	45,9	0,85	2,7	8,1
July	10,5	25,1	81,5	48,7	0,78	2,7	16,9
August	13,2	28,2	81,8	41,9	1,27	4,8	0,0
September	15,1	28,6	74,1	41,4	1,54	5,5	30,2
October	17,6	30,7	73,6	47,5	1,61	6,1	40,9

Appendix 2: Leaf emergence data

Table A2.1 Leaf emergence of varieties ZN6, ZN7, N14 and NCo376 recorded daily. DAP is days after planting and SE is standard error of the mean

Leaf	ZN6		ZN7		N14		NCo376	
number	DAP	SE	DAP	SE	DAP	SE	DAP	SE
1	27,00	0,00						
2	27,75	1,04	27,25	0,50	27,00	0,00	27,00	0,00
3	28,95	1,76	27,81	0,93	28,10	1,33	28,00	1,10
4	31,74	5,37	29,33	1,90	30,00	3,14	30,36	3,18
5	35,26	7,07	32,68	3,70	33,45	4,25	31,91	4,48
6	39,53	7,00	36,89	4,21	37,48	4,32	35,64	5,40
7	44,62	6,55	40,91	4,23	41,40	3,76	39,16	4,97
8	48,48	6,25	44,05	3,47	45,18	3,20	43,07	4,83
9	52,09	6,96	47,24	2,56	48,82	2,92	46,80	4,61
10	55,21	7,96	50,23	2,82	50,69	3,65	50,17	4,08
11	58,60	7,96	53,25	3,56	53,96	4,08	53,44	4,30
12	63,98	8,17	56,88	4,17	57,70	4,45	57,04	5,25
13	69,38	8,78	61,14	4,25	62,56	4,45	61,67	7,01
14	75,76	10,19	65,64	4,77	67,58	4,39	67,02	8,46
15	81,80	11,00	70,90	5,72	73,12	5,18	72,04	6,49
16	86,82	10,52	76,02	5,77	78,72	5,63	78,67	7,05
17	93,22	13,01	81,37	5,95	84,36	5,02	85,33	7,71
18	99,76	14,31	86,82	5,79	90,16	5,84	91,90	9,45
19	107,56	16,26	92,22	7,21	96,62	7,14	99,55	11,72
20	116,23	17,79	97,80	7,64	105,38	10,60	107,46	13,25
21	125,88	18,55	105,04	9,55	113,65	11,08	118,42	15,32
22	136,53	19,85	114,00	11,68	125,09	11,51	128,67	14,64
23	145,82	22,62	123,19	11,17	134,13	10,83	138,22	15,49
24	155,56	29,41	131,65	10,28	143,51	13,44	149,29	21,02
25	164,84	30,27	140,63	10,26	154,45	16,88	157,72	20,04
26	176,63	34,41	147,59	11,84	165,48	18,35	169,72	22,24
27	187,89	30,80	157,88	12,25	181,48	24,15	187,00	29,49
28	200,24	25,61	169,55	13,62	201,67	34,18	204,56	34,42
29	217,98	27,32	183,10	17,28	220,59	35,44	226,17	32,94
30	239,80	31,86	199,69	21,65	241,55	35,97	250,90	30,71
31	261,24	31,60	220,21	24,33	265,53	34,80	282,59	29,55
32	282,86	29,39	243,96	27,60	287,29	32,58	305,03	24,73
33	301,79	25,77	264,47	27,17	310,28	28,76	317,08	20,17
34	315,38	20,32	284,78	23,78	317,83	23,52	330,83	15,92
35	324,45	17,82	301,84	20,73	328,17	17,78	337,60	9,63
36	334,31	16,24	317,00	19,83	331,73	14,51	346,00	7,67
37	338,41	9,79	329,55	15,09	338,50	8,38	346,67	2,08
38	344,64	7,66	336,09	22,36	341,00	2,83		
39	346,50	3,42	342,71	8,58				
40			345,42	5,38				
41			351,20	1,79				

Table A2.2 Leaf emergence of varieties ZN6, ZN7, N14 and NCo376 recorded daily from 19 October 2001 to 19 October 2002. TT10 is the accumulated thermal time calculated using a base temperature of 10°C. SD is standard deviation

Leaf	ZN6		ZN7		N14		NCo376	
number	°C.day	SD	°C.day	SD	°C.day	SD	°C.day	SD
1	454,90	0,00						
2	467,21	17,03	459,16	8,53	454,90	0,00	454,90	0,00
3	487,47	29,53	468,34	15,26	473,42	22,34	471,67	18,36
4	533,68	87,12	493,71	31,70	504,75	51,62	510,94	53,08
5	591,04	114,08	549,66	61,51	562,26	69,56	535,85	72,73
6	659,89	112,03	617,65	67,07	627,71	68,78	597,41	86,68
7	739,48	102,95	681,28	65,61	689,31	57,01	654,34	77,72
8	799,74	99,82	730,37	53,08	747,41	49,90	715,51	74,91
9	857,88	111,07	779,60	40,89	805,27	47,06	773,40	73,39
10	908,28	128,52	827,94	45,94	835,09	59,33	827,22	66,62
11	964,38	128,83	876,58	57,91	889,11	66,74	879,91	70,42
12	1052,03	131,80	936,72	68,43	949,36	72,24	938,99	85,09
13	1136,73	140,49	1006,54	70,30	1028,89	71,00	1013,69	112,09
14	1234,94	164,11	1078,42	74,29	1110,26	66,12	1100,45	135,27
15	1330,97	181,96	1159,50	86,10	1192,62	78,59	1177,78	99,69
16	1413,30	175,21	1237,34	89,73	1279,47	90,90	1279,91	114,24
17	1520,86	215,43	1322,88	96,77	1371,48	84,73	1388,29	130,41
18	1631,43	234,55	1413,43	98,13	1469,88	99,80	1498,77	159,14
19	1761,62	261,29	1504,92	121,84	1580,27	121,10	1628,57	195,16
20	1904,38	282,66	1600,37	128,69	1727,00	175,20	1761,80	217,84
21	2059,55	281,18	1722,60	158,63	1864,58	180,63	1942,80	250,08
22	2228,70	278,53	1870,30	191,04	2051,86	188,40	2109,03	237,14
23	2374,34	296,39	2020,10	182,52	2198,24	176,40	2263,72	245,41
24	2514,65	354,63	2159,14	169,31	2350,88	212,96	2431,63	287,07
25	2653,28	342,01	2305,62	165,88	2518,84	245,05	2563,56	274,26
26	2816,42	373,96	2417,57	188,30	2682,41	252,02	2735,93	275,02
27	2969,52	329,26	2577,63	186,70	2890,93	283,92	2951,70	312,12
28	3113,37	265,49	2748,75	194,30	3115,67	337,34	3154,65	334,86
29	3295,32	252,51	2926,59	217,53	3313,07	329,82	3374,19	304,25
30	3495,89	269,55	3114,61	236,74	3501,22	308,59	3585,39	260,44
31	3680,44	272,64	3322,90	231,69	3714,22	297,86	3861,12	267,66
32	3862,92	265,28	3527,96	233,74	3911,34	302,83	4075,46	258,95
33	4042,02	258,24	3699,32	224,61	4141,15	295,03	4203,61	228,09
34	4186,79	221,05	3871,82	210,38	4217,70	260,19	4362,92	191,03
35	4287,54	197,70	4037,67	211,40	4331,03	203,69	4438,32	114,28
36	4406,30	191,26	4203,02	225,43	4373,26	173,63	4547,51	101,67
37	4449,72	119,00	4346,80	182,21	4451,92	99,21	4556,66	30,91
38	4527,82	103,87	4423,92	151,65	4475,75	40.94		
39	4553,15	49,18	4503,77	112,25				
40			4536,00	76,27				
41			4617,47	24,42				

Tables A2.3 The R^2 values of the regression lines for phyllochron interval 1 (P1) and phyllochron interval 2 (P2) for varieties ZN6, ZN7, N14 and NCo376. The P1 and P2 was calculated with break points ranging from leaf number 4 to leaf number 22. The leaf number opposite the highlighted R^2 values represent the leaf number where leaf emergence switches from phyllochron 1 to phyllochron 2. The leaf emergence data was collected from 19 October 2001 to 19 October 2002.

Leaf Number	ZN6		ZN7		N14		NCo376	
	P1	P2	P1	P2	P1	P2	P1	P2
4	0,0703	0,9428	0,1806	0,9404	0,1773	0,9288	0,1391	0,9202
5	0,2381	0,9435	0,2455	0,9420	0,3264	0,9306	0,1665	0,9216
6	0,4479	0,9443	0,4588	0,9443	0,5301	0,9333	0,3028	0,9232
7	0,6383	0,9456	0,6044	0,9472	0,6610	0,9355	0,4574	0,9246
8	0,7364	0,9467	0,7114	0,9501	0,7655	0,9389	0,5959	0,9261
9	0,7952	0,9471	0,7851	0,9523	0,8278	0,9408	0,6829	0,9266
10	0,8234	0,9466	0,8342	0,9541	0,8587	0,9413	0,7539	0,9262
11	0,8381	0,9446	0,8599	0,8824	0,8824	0,9409	0,8042	0,9238
12	0,8586	0,9420	0,8823	0,9550	0,8991	0,9390	0,8355	0,9197
13	0,8745	0,9385	0,9000	0,9548	0,9155	0,9359	0,8543	0,9137
14	0,8865	0,9340	0,9135	0,9541	**0,9270**	**0,9319**	0,8710	0,9052
15	0,8978	0,9280	0,9203	0,9528	0,9341	0,9262	0,8799	0,8946
16	0,9056	0,9204	0,9273	0,9502	0,9370	0,9186	**0,8848**	**0,8815**
17	**0,9124**	**0,9097**	0,9323	0,9464	0,9421	0,9075	0,8883	0,8648
18	0,9121	0,8974	0,9352	0,9411	0,9442	0,8925	0,8857	0,8451
19	0,9109	0,8826	**0,9331**	**0,9344**	0,9449	0,8717	0,8806	0,8225
20	0,9055	0,8678	0,9321	0,9253	0,9390	0,8459	0,8782	0,7940
21	0,9047	0,8497	0,9278	0,9152	0,9319	0,8165	0,8737	0,7684
22	0,9068	0,8273	0,9219	0,9052	0,9260	0,7799	0,8765	0,7364

Appendix 3: Leaf population data

Table A3.1 The total green leaf numbers per hectare of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT10 is the cumulative thermal time calculated using a base temperature of 10°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	571,20	268000	280000	305333	374667	44336
48	795,65	378667	420000	677333	838667	67027
60	988,05	758667	865333	954667	1348000	128702
75	1217,55	956000	966667	1714667	1814333	149631
89	1448,30	1192000	1301333	1836000	1772000	116708
103	1689,85	1252000	1145333	1894667	2108000	101225
124	2032,10	1297333	1082667	1380000	1625333	162740
131	2147,20	1521333	946667	1429333	1797333	115853
145	2375,70	1612000	1121333	1564000	2116000	200081
158	2589,10	1414667	1196000	1850667	1846667	123546
173	2808,70	1586667	1264000	1750666	1898667	108003
187	2992,00	1094667	1117333	1412000	1524000	85653
202	3165,95	1218667	1185333	1489333	1685333	136155
215	3283,60	1490667	1133333	1277334	1570667	139492
229	3429,45	1053333	1093333	1297333	1353334	84796
243	3541,80	1189333	1054667	1310667	1268000	144052
257	3638,20	1098667	1069333	1154667	1378667	80920
271	3748,65	1157333	738667	1061333	1356000	134004
285	3867,50	1245333	658667	1234667	1206667	92023
299	3987,95	1194667	964000	1109333	969333	106504
313	4150,55	1006667	908000	1181333	1214667	101168
327	4323,80	986667	992000	1253333	1445333	104523
341	4488,90	809333	916000	897333	985333	111477
355	4668.45	916000	950667	1086667	1140000	105854

Table A3.2 The fully emerged green leaf numbers per hectare of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT10 is the cumulative thermal time calculated using a base temperature of 10°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	571,20	221333	226667	264000	300000	40545
48	795,65	218667	233333	382667	490667	40707
60	988,05	392000	496000	518667	736000	67323
75	1217,55	484000	484000	932000	1042667	90675
89	1448,30	797334	805333	1229333	1232000	94615
103	1689,85	872000	818667	1329333	1518667	85179
124	2032,10	946667	868000	941333	1197333	124907
131	2147,20	1044000	692000	1018666	1324000	93038
145	2375,70	1149334	828000	1186667	1548000	141048
158	2589,10	1056000	958667	1362667	1406667	110998
173	2808,70	1188000	964000	1329333	1520000	85836
187	2992,00	826667	838667	1097333	1208000	76437
202	3165,95	948000	894667	1142667	1280000	105075
215	3283,60	1066667	852000	997333	1176000	123228
229	3429,45	762667	881333	950667	998667	75437
243	3541,80	852000	736000	981333	914667	116661
257	3638,20	845333	826667	821333	974667	73722
271	3748,65	818667	508000	754000	961333	117673
285	3867,50	880000	470667	881333	798667	72062
299	3987,95	805333	716000	792000	658667	82106
313	4150,55	764000	682667	849333	888000	77470
327	4323,80	745334	762667	789334	1030667	82741
341	4488,90	613333	648000	609333	705333	95413
355	4668.45	697333	709333	720000	844000	78732

Table A3.3 The emerging green leaf numbers per hectare of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT10 is the cumulative thermal time calculated using a base temperature of 10°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	571,20	45333	53334	44000	65333	8697
48	795,65	156000	186667	285333	340000	27241
60	988,05	286667	290667	337333	437333	45728
75	1217,55	312000	361333	578667	577333	79086
89	1448,30	394667	496000	606667	540000	62587
103	1689,85	380000	326667	565333	589333	70885
124	2032,10	350667	214667	438667	428000	54738
131	2147,20	477333	254667	410667	473333	27017
145	2375,70	462667	293333	377333	568000	64587
158	2589,10	358667	237333	488000	440000	43512
173	2808,70	398667	300000	421334	378667	31064
187	2992,00	268000	278667	314667	316000	29355
202	3165,95	270667	290667	346667	405333	36222
215	3283,60	424000	281333	280000	394667	32867
229	3429,45	290667	212000	346667	354667	26576
243	3541,80	337333	318667	329333	353333	42744
257	3638,20	253333	242667	333333	404000	21575
271	3748,65	338666	230667	306667	394667	35999
285	3867,50	365333	188000	353333	408000	30340
299	3987,95	289333	248000	317333	310667	40795
313	4150,55	242667	222667	332000	326667	29438
327	4323,80	241333	229333	464000	414667	46882
341	4488,90	196000	268000	288000	280000	27817
355	4668.45	218667	241333	366667	296000	32001

Table A3.4 The dead leaf numbers per hectare of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT10 is the cumulative thermal time calculated using a base temperature of 10°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	571,20	5333	9333	5333	8000	2969
48	795,65	22667	20000	46667	40000	7596
60	988,05	24000	26667	36000	32000	4595
75	1217,55	13333	12000	12667	17333	7577
89	1448,30	41333	61333	102667	61333	11835
103	1689,85	117333	157333	265333	393000	44958
124	2032,10	449333	401333	862667	1177333	144871
131	2147,20	746667	468000	896000	1402667	81038
145	2375,70	644000	602667	1226666	1277333	81678
158	2589,10	556000	689334	1340000	1276000	128116
173	2808,70	846667	833334	1310667	1298667	128273
187	2992,00	776000	990667	1294667	1332000	132118
202	3165,95	894667	1114667	1521333	2024000	157561
215	3283,60	1104000	1230667	1212000	1684000	148089
229	3429,45	985333	952000	1197333	1977333	119822
243	3541,80	1000000	962667	1580000	1953333	177727
257	3638,20	1416000	1521333	1900000	2484000	186403
271	3748,65	1465333	1524000	1780000	2405333	143625
285	3867,50	1940000	1489333	2177333	3041333	180851
299	3987,95	1509333	1434667	1774667	2341333	225773
313	4150,55	1340000	1660000	2037333	2585333	195541
327	4323,80	1728000	2072000	2494667	3616000	251746
341	4488,90	2228000	2221333	2777333	2717333	204877
355	4668.45	1974667	1945333	2425333	2701333	180859

Table A3.5 The total green leaf numbers per plant of varieties ZN6, ZN7, N14 and NCo376 recorded at weekly intervals from 19 October 2001 to 19 October 2002. SE mean is the standard error of the mean

Days after planting	ZN6	ZN7	N14	NCo376	SE mean
80	12,3	14,2	12,8	13,0	0,396
82	12,6	13,8	12,8	12,7	0,272
87	13,1	14,2	13,2	12,5	0,294
94	13,2	13,7	13,2	12,3	0,239
101	13,5	14,3	13,7	12,2	0,492
108	13,2	14,0	12,9	12,1	0,393
126	11,3	11,6	11,0	9,6	0,552
129	11,4	12,2	11,1	9,4	0,587
136	11,6	12,4	11,0	9,9	0,477
143	12,4	13,2	12,0	10,8	0,463
150	12,8	13,0	12,1	11,1	0,422
157	12,8	13,2	12,6	11,0	0,399
165	13,5	13,4	12,7	11,0	0,373
171	13,0	13,1	12,4	10,8	0,394
178	13,0	13,3	12,3	10,8	0,347
185	13,0	13,1	12,1	10,8	0,333
192	12,9	12,6	12,4	11,0	0,480
199	12,5	13,0	12,0	10,6	0,391
206	12,2	12,5	12,1	9,9	0,373
213	11,6	12,4	11,8	9,8	0,395
220	11,6	12,1	11,6	9,6	0,363
227	11,5	12,0	11,5	9,5	0,416
234	11,6	12,1	11,7	9,1	0,400
241	11,5	11,9	11,6	9,5	0,175
248	11,6	11,0	11,2	9,4	0,464
255	11,3	11,8	11,6	9,2	0,272
262	10,8	11,5	11,1	8,5	0,470
269	10,6	11,3	11,1	8,8	0,257
276	10,8	11,2	11,3	8,9	0,324
283	10,3	10,2	11,1	8,1	0,382
290	10,3	11,0	10,8	8,4	0,519
297	10,8	11,6	11,2	8,8	0,467
304	10,9	11,2	11,1	9,3	0,444
311	10,5	10,9	10,8	9,6	0,453
318	11,5	11,9	11,3	8,6	0,538
325	10,6	10,7	10,6	8,5	0,390
332	10,8	10,4	10,1	8,3	0,387
339	10,6	10,4	9,4	8,9	0,610
346	10.6	10.7	10.1	9,0	0,440
353	10.5	10.7	10.2	8.5	0,282

Appendix 4: Leaf angles and ELADP

Table A4.1 The mean leaf angles per plant (degrees) of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals. SE mean is the standard error of the mean

Days after planting	ZN6	ZN7	N14	NCo376	SE mean
92	37,7	49,3	37,3	34,3	1,182
105	44,2	57,0	43,4	40,0	1,114
126	34,1	48,4	31,6	27,7	1,799
133	38,1	49,7	33,2	32,3	1,491
147	36,2	50,7	33,0	31,1	0,749
160	38,0	49,2	36,2	34,1	1,581
175	39,8	48,3	39,1	35,1	0,873
189	43,2	51,5	38,4	37,1	1,262
203	40,0	49,1	40,0	33,0	1,498
217	42,2	51,0	39,1	37,7	2,076
231	37,3	48,5	41,7	33,5	2,764
245	38,1	48,0	38,3	37,8	2,136
259	35,5	46,6	38,3	36,7	2,478
273	36,4	50,3	45,2	30,6	3,373
287	35,1	47,1	36,1	28,7	1,929
301	36,7	42,1	37,3	31,0	2.773
315	39,6	54,7	47,3	39,2	1,829
329	37,9	51,0	43,2	35,8	2.440
343	42,2	48,2	39,3	40,1	1,766

Table A4.2 The ellipsoidal leaf angle distribution parameter (ELADP) of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals. SE mean is the standard error of the mean

Days after planting	ZN6	ZN7	N14	NCo376	SE mean
92	0,990	2,348	0,719	0,525	0,141
105	1,379	3,111	1,343	1,055	0,144
126	0,730	1,602	0,441	0,383	0,110
133	1,103	2,460	0,419	0,557	0,185
147	1,043	2,084	0,624	0,535	0,095
160	1,032	2,152	0,750	0,649	0,151
175	1,303	1,471	1,071	0,900	0,094
189	1,529	1,889	1,037	0,891	0,187
203	1,121	1,830	1,367	0,644	0,164
217	1,297	2,459	1,383	0,914	0,232
231	0,985	2,130	1,256	0,755	0,256
245	1,020	2,208	1,034	0,971	0,259
259	0,842	1,627	1,027	0,907	0,227
273	0,804	2,385	1,650	0,459	0,273
287	0,880	2,166	0,836	0,432	0,254
301	0,907	1,571	0,963	0,429	0,284
315	0,910	2,616	1,877	1,043	0,172
329	1,031	2,231	1,223	0,886	0,225
343	1,250	1,775	1,029	1,156	0,192

Appendix 5: Tillers and stalks ha^{-1}, tiller, stalk, canopy heights and internodes per stalk

Table A5.1 The tiller numbers per hectare of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	361,20	53333	53334	60000	69333	7449
48	498,65	62666	64000	125333	164000	12159
60	622,05	117333	113333	137334	217333	15868
75	761,55	125333	109333	208000	226667	20575
89	908,30	133333	124000	209333	198667	15263
103	1065,85	135600	97000	195800	219600	16546
124	1282,10	145333	97333	168000	198666	16269
131	1355,20	164000	82667	170667	200000	11966
145	1499,70	145333	90667	165333	204000	16028
158	1635,10	113333	97333	164000	181333	11052
173	1764,70	122667	110667	138667	173333	9832
187	1864,00	93333	92000	118667	138667	7076
202	1947,95	97333	94667	132000	173333	12605
215	1987,60	129333	98667	112000	177333	10978
229	2050,75	93333	84000	109333	146667	5571
243	2079,35	96000	73333	113333	141333	7874
257	2095,95	98667	89333	108000	162667	7034
271	2124,40	114667	76000	108000	157333	12208
285	2163,4	117333	72000	113333	166667	9649
299	2199,85	110667	85333	114667	152000	14084
313	2279,45	89333	88000	114666	133333	10223
327	2368,70	89333	94667	132000	164000	8344
341	2443,80	86667	78667	108000	121333	9416
355	2545.35	94667	88000	118667	130667	10694

Table A5.2 The tiller heights (cm) of varieties ZN6, ZN7, N14 and NCo376 measured at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean (cm)

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	361,20	11,6	11,0	11,7	10,1	0,906
48	498,65	18,3	17,1	15,7	13,9	1,064
60	622,05	22,5	23,5	22,6	21,0	2,191
75	761,55	35,2	37,5	32,7	38,4	2,361
89	908,30	52,6	56,3	50,1	53,8	3,467
103	1065,85	84,2	103,4	72,6	90,0	7,293
124	1282,10	104,4	120,7	94,9	127,2	7,592
131	1355,20	120,6	145,3	107,6	143,0	7,243
145	1499,70	142,4	177,1	130,3	160,3	7,585
158	1635,10	169,3	185,8	160,6	184,3	6,624
173	1764,70	205,1	213,8	182,0	210,5	5,745
187	1864,00	221,4	230,1	218,1	221,6	7,907
202	1947,95	232,2	241,6	202,8	229,4	6,118
215	1987,60	234,4	242,4	216,4	236,5	9,136
229	2050,75	231,1	235,7	243,8	245,0	9,217
243	2079,35	239,6	251,9	237,3	245,9	9,125
257	2095,95	249,9	260,3	252,3	249,0	9,140
271	2124,40	247,0	260,1	249,1	258,4	4,471
285	2163,4	246,5	250,6	258,0	257,1	7,126
299	2199,85	257,7	279,3	254,1	254,9	7,124
313	2279,45	262,2	272,8	260,8	261,2	5,448
327	2368,70	277,8	273,1	285,0	269,1	8,423
341	2443,90	266,1	299,6	253,0	265,5	10,467
355	2545,35	265,3	284,4	270,7	261,5	12,533

Table A5.3 The canopy heights (cm) of varieties ZN6, ZN7, N14 and NCo376 measured at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean (cm)

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
34	361,20	48,6	41,4	44,0	44,6	5,741
48	498,65	86,0	65,4	69,0	81,2	4,385
60	622,05	99,8	89,6	90,4	91,4	3,701
75	761,55	122,2	117,4	115,6	123,6	3,844
89	908,30	171,2	163,6	173,0	171,4	5,213
103	1065,85	212,4	237,8	223,4	219,2	4,745
124	1282,10	236,0	240,8	240,4	249,6	7,162
131	1355,20	255,0	274,8	255,0	257,0	5,758
145	1499,70	285,6	309,6	293,8	276,6	6,681
158	1635,10	296,6	324,6	300,2	302,8	6,878
173	1764,70	328,4	340,2	323,6	326,0	4,933
187	1864,00	342,8	363,0	354,0	343,0	6,455
202	1947,95	369,2	404,2	382,0	362,6	7,034
215	1987,60	367,4	396,8	382,4	368,8	5,265
229	2050,75	378,6	396,0	385,0	373,0	5,557
243	2079,35	386,8	416,0	406,2	387,4	6,263
257	2095,95	383,2	394,8	402,6	378,8	6,276
271	2124,40	386,0	401,0	418,2	400,4	6,425
285	2163,40	371,6	376,6	403,0	376,4	8,312
299	2199,85	388,2	394,6	402,8	367,0	11,143
313	2279,45	379,6	385,2	398,6	362,8	10,417
327	2368,70	380,4	382,6	412,0	368,2	8,866
341	2443,80	372,8	382,2	388,0	362,0	6,684
355	2545.35	389,4	405,6	408,4	380,0	11,059

Table A5.4 The stalk numbers of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
75	761,55	32000	41333	66667	86667	13225
89	908,30	94667	82667	126667	144000	8097
103	1065,85	109333	89333	142667	193333	10143
124	1282,10	117333	98667	148000	196000	19898
131	1355,20	136000	77333	145333	189333	8375
145	1499,70	137333	86666	138667	200000	17034
158	1635,10	108000	92000	156000	180000	11738
173	1764,70	122667	110667	138667	173333	9832
187	1864,00	93333	90667	125333	142667	7019
202	1947,95	97333	94667	132000	173333	12605
215	1987,60	129333	98667	112000	177333	10978
229	2050,75	93333	84000	109333	148000	5676
243	2079,35	96000	74667	118667	146667	7770
257	2095,95	98667	89333	108000	164000	6992
271	2124,40	118667	84000	109333	158667	12284
285	2163,4	117333	72000	113333	166667	9649
299	2199,85	110667	85333	114667	153333	13676
313	2279,45	92000	92000	116000	154667	12734
327	2368,70	89333	94667	132000	164000	8344
341	2443,80	86667	78667	108000	121333	9416
355	2545.35	94667	88000	118667	130667	10694

Table A5.5 The stalk heights (cm) of varieties ZN6, ZN7, N14 and NCo376 measured at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean (cm)

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
75	761,55	11,7	17,3	11,3	18,2	1,247
89	908,30	23,6	24,0	24,9	24,5	2,319
103	1065,85	48,3	63,1	40,0	51,7	4,002
124	1282,10	73,8	86,3	59,8	83,1	5,052
131	1355,20	95,6	107,3	76,8	107,6	5,115
145	1499,70	101,7	134,3	92,2	115,4	6,383
158	1635,10	129,2	147,1	116,1	139,9	4,533
173	1764,70	160,3	169,3	134,0	162,8	5,645
187	1864,00	171,5	179,4	153,2	170,2	6,757
202	1947,95	189,1	196,9	156,1	186,1	5,690
215	1987,60	191,7	200,9	168,0	195,0	7,694
229	2050,75	195,6	200,9	196,9	203,1	7,290
243	2079,35	196,3	205,5	179,7	198,1	7,869
257	2095,95	210,3	219,1	208,9	208,4	8,409
271	2124,40	205,4	207,7	202,7	217,4	6,890
285	2163,4	215,5	218,5	216,9	223,8	6,524
299	2199,85	221,9	243,4	212,7	219,4	6,929
313	2279,45	232,9	234,3	225,3	223,1	6,307
327	2368,70	246,0	239,1	247,3	235,2	8,320
341	2443,80	250,2	262,3	247,8	237,2	7,890
355	2545,35	249,0	258,3	249,4	236,1	7,937

Table A5.6 The internode numbers per stalks of varieties ZN6, ZN7, N14 and NCo376 recorded at fortnightly intervals from 19 October 2001 to 19 October 2002. TT16 is the cumulative thermal time calculated using a base temperature of 16°C. SE mean is the standard error of the mean

Days after planting	°C.day	ZN6	ZN7	N14	NCo376	SE mean
75	761,55	2,45	3,41	2,61	3,30	0,179
89	908,30	2,60	2,97	3,19	2,94	0,201
103	1065,85	3,81	5,18	3,97	4,69	0,228
124	1282,10	5,41	6,99	5,70	6,63	0,288
131	1355,20	6,95	8,08	6,50	8,23	0,271
145	1499,70	7,64	10,60	7,87	9,15	0,284
158	1635,10	9,10	11,10	9,55	10,20	0,233
173	1764,70	11,16	12,79	10,82	11,87	0,332
187	1864,00	11,25	13,28	10,89	12,50	0,424
202	1947,95	13,14	14,44	11,94	12,95	0,370
215	1987,60	13,73	15,23	12,82	14,37	0,450
229	2050,75	14,35	15,58	15,78	15,83	0,519
243	2079,35	14,23	15,63	14,28	14,24	0,481
257	2095,95	15,55	16,78	15,01	15,53	0,457
271	2124,40	15,20	16,01	15,75	16,65	0,476
285	2163,4	17,24	18,32	18,08	17,94	0,417
299	2199,85	16,83	19,93	17,49	17,17	0,327
313	2279,45	18,40	19,32	17,58	16,96	0,399
327	2368,70	18,97	20,67	18,69	18,76	0,587
341	2443,80	19,77	23,22	20,25	20,22	0,371
355	2545,35	22,93	24,05	21,02	22,02	0,429

Appendix 6: Leaf area data

Table A6.1 Leaf areas (cm^2) of individual leaves of varieties ZN6, ZN7, N14 and N14. The leaf areas were measured with a Delta-T leaf area meter

Leaf	Leaf area per leaf (cm^2)				Standard deviations			
number	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
1	17,50	34,00	31,00	15,67	12,02	18,38	0.00	6,43
2	36,00	47,40	36,33	42,92	15,25	19,19	15,95	22,81
3	83,54	82,56	85,40	63,28	38,42	46,47	28,79	28,58
4	120,53	142,31	120,41	84,13	44,58	54,05	39,46	38,84
5	169,81	200,07	142,60	105,72	60,84	76,44	53,16	43,00
6	214,42	234,36	178,70	134,36	59,99	77,78	57,55	48,26
7	246,88	272,57	198,35	155,92	68,30	74,64	77,86	51,10
8	281,24	291,52	218,92	176,09	66,72	85,81	89,48	59,41
9	303,00	312,38	247,31	192,71	70,00	86,07	87,91	63,49
10	312,23	355,25	274,11	205,61	63,21	73,51	91,34	60,98
11	334,41	370,58	310,58	205,79	60,40	69,36	78,60	50,98
12	369,94	387,53	317,45	247,00	48,43	61,82	72,25	80,55
13	370,00	359,67	343,20	279,13	66,99	57,91	76,22	89,71
14	387,92	351,31	359,40	351,00	71,11	60,36	77,81	46,84
15	420,90	382,11	401,56	355,29	30,49	61,46	79,02	54,56
16	422,70	403,42	404,53	352,25	38,56	61,19	80,63	45,04
17	417,90	400,36	428,92	333,78	44,18	77,47	75,93	66,60
18	407,20	409,55	457,78	322,78	48,82	87,69	52,94	83,30
19	407,70	403,70	439,67	320,10	42,71	92,73	60,82	56,75
20	397,80	408,89	454,71	329,17	36,81	75,71	30,63	34,79
21	378,56	395,89	430,86	318,00	31,07	75,18	33,54	70,30
22	380,14	408,25	414,20	349,50	25,03	51,79	24,51	78,49
23	356,00	387,00	373,50	340,00	21,70	43,98	43,13	108,89
24	328,50	361,00	385,00	262,00	6,36	58,67	0,00	0,00
25	360,00	344,50				89,80		

Table A6.2 The leaf area index (LAI) of varieties ZN6, ZN7, N14 and NCo376 measured fortnightly from 19 October 2001 to 19 October 2002. TT10 and TT16 are the cumulative thermal time calculated with base temperatures of 10°C and 16°C. SE mean is the standard error of the mean

Days after planting	TT10	TT16	ZN6	ZN7	N14	NCo376	S.E. mean
34	571,20	361,20	0,065	0,062	0,082	0,082	0,014
48	795,65	498,65	0,117	0,109	0,194	0,206	0,028
60	988,05	622,05	0,290	0,443	0,474	0,499	0,076
75	1217,55	761,55	0,747	0,931	1,116	1,158	0,133
89	1448,30	908,30	1,195	1,415	1,657	1,421	0,150
103	1689,85	1065,85	2,426	2,442	2,992	3,361	0,402
124	2032,10	1282,10	2,774	2,428	2,951	3,270	0,262
131	2147,20	1355,20	2,856	1,813	2,755	3,254	0,259
145	2375,70	1499,70	4,178	3,333	4,471	4,304	0,404
158	2589,10	1635,10	3,401	3,124	5,263	4,720	0,360
173	2808,70	1764,70	3,887	3,317	4,472	4,071	0,277
187	2992,00	1864,00	2,851	2,879	4,433	3,377	0,229
202	3165,95	1947,95	3,380	2,835	4,212	3,553	0,311
215	3283,60	1987,60	1,684	1,896	1,667	2,471	0,261
229	3429,45	2050,75	2,913	2,454	4,307	3,100	0,185
243	3541,80	2079,35	3,716	2,606	4,940	3,229	0,402
257	3638,20	2095,95	3,421	3,073	4,357	3,620	0,348
271	3748,65	2124,40	3,553	1,953	3,676	2,859	0,314
285	3867,50	2163,40	3,535	1,541	4,146	2,373	0,353
299	3987,95	2199,85	3,119	2,242	3,641	1,763	0,289
313	4150,55	2279,45	2,964	2,068	3,854	2,175	0,305
327	4323,80	2368,70	2,473	2,039	3,790	2,436	0,280
341	4488,90	2443,80	2,158	2,003	2,728	1,636	0,306
355	4668,45	2545,35	1,524	1,229	1,833	0,951	0,157

Appendix 7: Model evaluation data for CANEGRO version 1 and version 2.

Table A7.1 The observed and predicted (CANEGRO canopy models version 1 and version 2) tiller heights (m) for varieties ZN6, ZN6, N14 and NCo376

	Observed tiller heights (m)				Predicted by version 1 (m)				Predicted by Version 2 (m)			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
34	0,12	0,11	0,12	0,10	0,09	0,09	0,09	0,09	0,20	0,20	0,20	0,20
48	0,18	0,17	0,16	0,14	0,24	0,24	0,24	0,24	0,35	0,35	0,35	0,35
60	0,23	0,23	0,23	0,21	0,37	0,36	0,36	0,36	0,48	0,48	0,48	0,47
75	0,35	0,38	0,33	0,38	0,51	0,50	0,50	0,50	0,63	0,63	0,62	0,62
89	0,53	0,56	0,50	0,54	0,66	0,65	0,65	0,65	0,79	0,79	0,78	0,77
103	0,84	1,03	0,73	0,90	0,82	0,82	0,82	0,82	0,95	0,95	0,94	0,94
124	1,04	1,21	0,95	1,27	1,06	1,04	1,04	1,04	1,19	1,19	1,16	1,15
131	1,21	1,45	1,08	1,43	1,11	1,10	1,10	1,10	1,25	1,25	1,21	1,20
145	1,42	1,77	1,30	1,60	1,26	1,24	1,24	1,24	1,41	1,40	1,36	1,35
158	1,69	1,86	1,61	1,84	1,41	1,39	1,39	1,39	1,55	1,55	1,51	1,50
173	2,05	2,14	1,82	2,10	1,56	1,54	1,54	1,54	1,70	1,70	1,66	1,65
187	2,21	2,30	2,18	2,22	1,68	1,67	1,67	1,67	1,83	1,82	1,78	1,77
202	2,32	2,42	2,03	2,29	1,80	1,78	1,78	1,78	1,94	1,94	1,90	1,89
215	2,34	2,42	2,16	2,37	1,88	1,86	1,86	1,86	2,02	2,02	1,98	1,97
229	2,31	2,36	2,44	2,45	1,98	1,97	1,97	1,97	2,13	2,12	2,08	2,07
243	2,40	2,52	2,37	2,46	2,06	2,05	2,05	2,05	2,21	2,20	2,16	2,15
257	2,50	2,60	2,52	2,49	2,13	2,11	2,11	2,11	2,27	2,27	2,23	2,22
271	2,47	2,60	2,49	2,58	2,21	2,19	2,19	2,19	2,35	2,35	2,31	2,30
285	2,46	2,51	2,58	2,57	2,29	2,27	2,27	2,27	2,43	2,43	2,39	2,38
299	2,58	2,79	2,54	2,55	2,37	2,36	2,36	2,36	2,52	2,51	2,47	2,46
313	2,62	2,73	2,61	2,61	2,49	2,47	2,47	2,47	2,63	2,63	2,59	2,58
327	2,78	2,73	2,85	2,69	2,61	2,59	2,59	2,59	2,75	2,75	2,71	2,70
341	2,66	3,00	2,53	2,65	2,71	2,69	2,69	2,69	2,85	2,85	2,81	2,80
355	2,65	2,84	2,71	2,62	2,84	2,82	2,82	2,82	2,98	2,98	2,94	2,93

Table A7.2 The observed and predicted (CANEGRO canopy models version 1 and version 2) tillers m^{-2} population for varieties ZN6, ZN6, N14 and NCo376

	Observed tillers m^{-2}				Predicted by Version 1 (tillersm^{-2})				Predicted by version 2 (tillersm^{-2})			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
34	5,33	5,33	6,00	6,93	6,43	6,43	6,43	6,43	3,74	3,17	4,97	6,33
48	6,27	6,40	12,53	16,40	15,40	15,40	15,40	15,40	6,60	5,48	8,80	11,00
60	11,73	11,33	13,73	21,73	20,90	21,14	21,14	21,14	9,34	7,67	12,10	16,50
75	12,53	10,93	20,80	22,67	22,10	22,35	22,35	22,35	12,64	10,33	16,39	22,88
89	13,33	12,40	20,93	19,87	22,10	22,35	22,35	22,35	15,24	12,06	20,61	21,74
103	13,60	9,73	19,60	22,00	20,04	20,29	20,29	20,29	14,89	12,03	19,67	20,73
124	14,53	9,73	16,80	19,87	13,30	13,30	13,30	13,30	14,49	11,99	18,61	19,56
131	16,40	8,27	17,07	20,00	13,30	13,30	13,30	13,30	14,38	11,98	18,29	19,21
145	14,53	9,07	16,53	20,40	13,30	13,30	13,30	13,30	14,17	11,97	17,73	18,58
158	11,33	9,73	16,40	18,13	13,30	13,30	13,30	13,30	14,00	11,95	17,29	18,09
173	12,27	11,07	13,87	17,33	13,30	13,30	13,30	13,30	13,86	11,84	16,91	17,68
187	9,33	9,20	11,87	13,87	13,30	13,30	13,30	13,30	13,77	11,93	16,67	17,40
202	9,73	9,47	13,20	17,33	13,30	13,30	13,30	13,30	13,69	11,93	16,47	17,18
215	12,93	9,87	11,20	17,73	13,30	13,30	13,30	13,30	13,66	11,93	16,38	17,08
229	9,33	8,40	10,93	14,67	13,30	13,30	13,30	13,30	13,61	11,92	16,24	16,92
243	9,60	7,33	11,33	14,13	13,30	13,30	13,30	13,30	13,58	11,92	16,17	16,85
257	9,87	8,93	10,80	16,27	13,30	13,30	13,30	13,30	13,57	11,92	16,13	16,81
271	11,47	7,60	10,80	15,73	13,30	13,30	13,30	13,30	13,54	11,92	16,07	16,74
285	11,73	7,20	11,33	16,67	13,30	13,30	13,30	13,30	13,52	11,92	16,00	16,66
299	11,07	8,53	11,47	15,33	13,30	13,30	13,30	13,30	13,49	11,91	15,93	16,59
313	9,20	9,20	11,60	15,47	13,30	13,30	13,30	13,30	13,44	11,91	15,79	16,42
327	8,93	9,47	13,20	16,40	13,30	13,30	13,30	13,30	13,39	11,91	15,65	16,28
341	8,67	7,87	10,80	12,13	13,30	13,30	13,30	13,30	13,35	11,90	15,56	16,17
355	9,47	8,80	11,87	13,07	13,30	13,30	13,30	13,30	13,30	11,90	15,41	16,01

Table A7.3 The observed and predicted (CANEGRO canopy models version 1 and version 2) leaf area index for varieties ZN6, ZN6, N14 and NCo376

	Observed LAI				LAI Predicted by version 1				LAI Predicted by version 2			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
34	0,060	0,062	0,082	0,084	0,01	0,01	0,01	0,01	0,02	0,02	0,03	0,03
48	0,116	0,106	0,194	0,206	0,09	0,11	0,11	0,11	0,10	0,11	0,16	0,18
60	0,292	0,444	0,474	0,498	0,32	0,39	0,39	0,39	0,25	0,27	0,39	0,45
75	0,748	0,932	1,116	1,160	0,92	1,15	1,15	1,15	0,58	0,62	0,92	1,11
89	1,196	1,416	1,658	1,420	1,95	2,40	2,40	2,28	1,14	1,14	1,64	1,83
103	2,428	2,442	2,990	3,362	3,24	3,85	3,85	3,62	1,89	1,72	2,47	2,42
124	2,772	2,426	2,952	3,268	3,95	3,87	3,87	3,51	2,94	2,54	3,32	3,45
131	2,856	1,814	2,754	3,252	4,05	4,32	4,34	3,94	3,13	2,67	3,73	3,97
145	4,178	3,332	4,470	4,304	4,62	5,20	5,35	4,58	3,85	3,37	4,75	4,91
158	3,402	3,124	5,264	4,718	5,12	5,61	5,89	4,82	4,40	3,95	5,60	5,48
173	3,888	3,318	4,470	4,072	5,26	5,50	5,87	4,55	4,45	3,99	5,75	5,11
187	2,852	2,880	4,434	3,378	5,52	5,63	6,07	4,59	4,67	4,16	6,01	5,17
202	3,380	2,836	4,212	3,552	5,71	5,68	6,20	4,63	4,81	4,22	6,19	5,19
229	2,912	2,452	4,308	3,100	6,18	5,59	6,21	4,53	5,27	4,08	6,12	4,99
243	3,716	2,608	4,94	3,230	6,09	5,97	6,64	4,85	5,15	4,42	6,62	5,39
257	3,42	3,072	4,356	3,622	5,93	5,82	6,48	4,72	4,93	4,23	6,37	5,18
271	3,552	1,952	3,678	2,860	6,30	5,71	6,36	4,63	5,31	4,08	6,20	5,01
285	3,532	1,540	4,146	2,372	6,19	6,11	6,81	4,97	5,16	4,44	6,72	5,43
299	3,118	2,242	3,642	1,764	6,10	6,03	6,71	4,88	5,02	4,32	6,56	5,27
313	2,964	2,068	3,852	2,178	6,65	6,55	7,28	5,35	5,04	4,35	6,60	5,25
327	2,474	2,038	3,790	2,436	6,68	6,58	7,32	5,36	5,04	4,36	6,63	5,23
341	2,160	2,004	2,728	1,638	6,62	6,52	7,25	5,30	4,98	4,31	6,55	5,15
355	1,526	1,232	1,832	0,952	6,73	6,.63	7,36	5,38	5,06	4,40	6,67	5,21

Table A7.4 The observed and predicted (CANEGRO canopy models version 1 and version 2) green leaf number per stalk for varieties ZN6, ZN6, N14 and NCo376

	Observed green leaf numbers				Predicted by version 1				Predicted by version 2			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
34	5,257	5,176	5,022	5,384	1,34	1,34	1,34	1,34	2,77	3,39	3,22	2,91
48	6,186	6,482	5,426	5,166	2,86	3,14	3,14	3,14	4,17	4,81	4,50	4,30
60	6,466	7,526	6,895	6,192	4,47	5,06	5,06	5,06	5,36	6,16	6,00	5,47
75	8,036	9,092	8,315	8,139	7,18	8,17	8,17	8,17	6,83	7,55	7,41	6,75
89	8,978	10,581	8,889	8,935	9,82	9,87	9,87	8,92	8,10	8,30	6,77	6,84
103	9,438	11,923	9,829	9,745	10,68	10,84	10,84	9,86	8,90	8,48	7,54	6,49
124	9,314	11,375	8,322	8,137	12,01	11,77	11,76	10,93	9,30	8,85	8,06	8,22
131	9,268	11,342	8,573	8,954	11,75	11,84	11,83	10,84	9,28	8,75	8,16	8,46
145	11,286	12,556	9,461	10,200	12,16	12,33	12,34	11,33	9,83	9,62	9,27	9,47
158	12,516	12,353	11,340	10,236	12,50	12,58	12,58	11,58	10,33	10,18	10,07	10,03
173	12,956	11,628	12,805	10,953	11,76	11,84	11,84	10,83	9,57	9,71	9,62	9,45
187	11,802	12,159	11,878	11,062	11,84	12,00	12,00	11,00	9,91	9,70	9,77	9,49
202	12,614	12,709	11,346	9,748	11,92	12,00	12,00	11,00	9,92	9,79	9,97	9,68
215	11,603	11,408	11,354	8,839	11,67	11,75	11,76	10,75	10,41	9,61	9,67	9,34
229	11,428	13,101	11,998	9,283	12,50	11,67	11,67	10,67	10,42	9,45	9,65	9,30
243	12,286	14,175	11,585	8,921	12,25	12,33	12,33	11,33	10,02	10,16	10,21	9,91
257	11,254	12,138	10,727	8,478	11,84	11,92	11,92	10,91	9,79	9,70	9,96	9,57
271	10,093	9,936	9,868	8,596	12,50	11,67	11,67	10,67	10,44	9,45	9,71	9,32
285	10,571	9,159	10,931	7,293	12,33	12,49	12,49	11,49	10,04	10,17	10,35	10,00
299	11,225	11,432	9,702	6,535	11,92	12,00	12,00	11,00	9,96	9,80	10,24	9,74
313	11,255	9,883	10,346	7,970	13,00	13,00	13,00	12,00	9,97	9,80	10,30	9,76
327	10,977	10,620	9,515	8,734	13,00	13,00	13,00	12,00	9,98	9,89	10,35	9,84
341	9,675	11,830	8,242	8,100	13,00	13,00	13,00	12,00	10,00	9,80	10,32	9,79
355	10,081	10,803	9,138	8,780	13,00	13,00	13,00	12,00	10,00	9,89	10,45	9,87

Table A7.5 The observed and predicted (CANEGRO canopy models version 1 and version 2) dead leaf number per stalk for varieties ZN6, ZN6, N14 and NCo376

	Observed dead leaf numbers				Predicted by version 1				Predicted by version 2			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
34	0,070	0,166	0,079	0,107	0	0	0	0	0	0	0	0
48	0,319	0,324	0,368	0,231	0	0	0	0	0	0	0	0
60	0,227	0,284	0,280	0,150	0	0	0	0	0	0	0	0
75	0,111	0,141	0,107	0,084	0	0	0	0	0	0,15	0,10	0,36
89	0,320	0,484	0,509	0,319	0,36	1,50	1,50	2,45	0,47	1,54	2,08	3,83
103	0,979	1,614	1,319	1,765	2,88	3,98	3,98	4,95	2,67	4,55	4,48	7,19
124	3,125	4,020	5,119	5,761	4,99	8,05	8,06	9,06	5,70	8,38	7,49	10,11
131	4,708	5,725	5,345	7,013	5,99	8,98	8,99	9,98	6,84	9,48	8,37	10,95
145	4,272	6,653	7,502	6,416	6,99	9,99	9,99	10,99	7,96	10,89	9,52	11,96
158	4,941	6,839	8,192	7,253	7,99	10,99	10,99	11,99	8,97	11,96	10,66	12,97
173	6,867	7,624	9,441	7,454	9,99	12,99	12,99	13,99	10,97	13,96	12,72	14,98
187	8,218	10,883	10,845	9,716	10,99	13,99	13,99	14,99	11,97	14,97	13,84	15,98
202	9,219	11,981	11,878	11,630	11,99	14,99	14,99	15,99	12,97	15,97	14,94	16,98
215	8,528	12,856	10,932	9,532	12,99	15,99	15,99	16,99	12,97	16,97	15,96	17,98
229	10,553	11,321	10,922	13,407	12,99	16,99	16,99	17,99	13,97	17,97	17,05	18,98
243	10,301	13,262	13,986	13,963	13,99	17,00	17,00	18,00	14,97	17,97	17,12	18,98
257	14,538	17,258	17,736	15,297	14,99	17,99	17,99	18,99	15,97	18,97	18,11	19,98
271	12,979	21,024	17,343	16,231	14,99	18,99	18,99	19,99	15,97	19,97	19,14	20,98
285	16,536	20,821	19,301	18,291	15,99	19,00	18,99	19,99	16,97	19,97	19,23	20,98
299	13,457	17,084	15,674	15,055	16,99	19,99	19,99	20,99	17,97	20,97	20,28	21,98
313	15,527	17,961	18,058	16,928	18,00	21,00	21,00	22,00	18,97	21,97	21,44	22,98
327	19,958	22,050	19,301	22,032	19,00	22,00	22,00	23,00	19,97	22,97	22,60	23,98
341	26,322	30,836	25,678	22,450	20,00	23,00	23,00	24,00	20,97	23,97	23,73	24,98
355	22,980	22,352	21,048	21,054	21,00	24,00	24,00	25,00	21,97	24,97	24,95	25,98

Table A7.6 The observed and predicted (CANEGRO canopy models version 1 and version 2) intercepted PAR (%) for varieties ZN6, ZN6, N14 and NCo376

	Observed intercepted PAR				Predicted by version 1				Predicted by version 2			
DAP	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376	ZN6	ZN7	N14	NCo376
87	39,52	50,22	67,42	53,72	76	84	84	82	59	59	74	79
95	45,60	58,26	72,18	65,38	89	95	95	94	71	70	82	86
102	56,66	64,08	79,84	70,36	96	99	99	99	79	77	89	89
109	67,14	67,92	83,24	79,84	99	99	99	99	85	81	92	95
116	70,05	74,35	89,83	73,73	99	99	99	99	91	87	98	99
124	67,22	74,44	79,94	76,86	99	99	99	99	95	91	98	99
131	71,80	70,36	85,58	78,56	99	99	99	99	97	92	99	99
144	83,48	81,62	90,10	87,90	99	99	99	99	99	98	99	99
157	93,78	92,46	95,60	96,52	99	99	99	99	99	99	99	99