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Report to the

Water Research Commission and the Department of Agriculture, Forestry and Fisheries

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EXECUTIVE SUMMARY

1. BACKGROUND AND MOTIVATION

The need for increased food and timber production due to population increases and economic development has led to substantial increases in land under irrigated agriculture and forestry in South Africa (SA) over the past 50 years. Under current development trajectories, SA is expected to experience particularly severe water shortages in the future. Consequently, the competition for water between different users has increased. This is urging regulators of water supplies to find solutions to alleviate this growing pressure on water resources. In addition, compliance with relevant legislation embodied in the National Water Act (DWAF, 1998) and the meeting of international trans-boundary water supply obligations are mandatory. One of the longterm solutions lies in understanding how, and improving the efficiency with which water is used, reducing wastage and ensuring that unnecessary "water exports" are avoided. A good understanding of the water use of the major land uses is key to assessing and improving the efficient use of water. The National Water Act (1998) (DWAF, 1998) clearly states that water should be used efficiently.

The area registered for irrigation use in SA is 1 675 882 ha (Van der Stoep *et al*., 2008). It is estimated that this sector uses between 59 (Backeberg, 2005) and 63 % (Water Accounts for South Africa, 2000 and Reinders, 2010) of South Africa's water resources, so improving the water use efficiency (WUE) without expansion can potentially contribute to water savings and food security. As water use for agriculture is subject to increasing scrutiny from policy makers and environmentalists, the result is that the industry is under increasing pressure to demonstrate that water is being used efficiently.

Numerous methods are available to provide information on crop water use (or evapotranspiration, ET), crop irrigation requirements, biomass and yield production and efficiency with which crops area produced, or water use efficiency (WUE). Of these, field level methods (e.g. lysimeters, Eddy covariance, Bowen Ratio, surface renewal, scintillometry, soil water balance) used to estimate (or measure) evapotranspiration (ET) from surfaces have been evaluated extensively in past Water Research Commission funded projects. Similarly numerous models have been developed in SA (e.g. SWB, SAPWAT, BEWAB, CANESIM®) to estimate crop water use and crop irrigation water requirements from agricultural fields and these have also been evaluated in past WRC funded projects. All these methods typically have the limitations that: (1) they do not provide a picture of the spatial variation in e.g. crop water use across and in between agricultural fields or an area; and (2) some of these methods are currently not widely applied operationally to assist farmers and other users in agricultural water management. Advances in recent years in the use of remote sensing (RS) information makes it now possible to assess crop water use, biomass and yield production (and WUE) spatially for each pixel (< 30 to 1000 m) of a satellite image or irrigated block. Spatially explicit methods have the potential to contribute greatly towards improved water management from field to regional level. Different methods have been developed to provide information at a range of temporal and spatial scales and hence for different applications. For agricultural (field scale) applications a number of models have been developed, including the Surface Energy Balance Algorithm for Land (SEBAL) model. The SEBAL model has been applied operationally for field scale agricultural water management and has been evaluated extensively, locally and internationally.

Using spatial data products related to crop growth, yield and water and nutrient use to evaluate farming practices of major agricultural crops can yield valuable information to assist in assessing the WUE of crops and identifying problem areas in terms of suboptimal yield. Maize and sugarcane are both cultivated extensively under irrigation in South Africa. Although the majority of the area under sugarcane relies on rainfall and only 24% of the area under cane is irrigated, irrigated sugarcane is perceived as a high water user. The Mpumalanga (Komatipoort and Malelane) and Pongola sugarcane production areas are fully irrigated. Whilst only representing about 16% of the total area under sugarcane cane, it produces almost 30% of the total annual sugarcane crop emphasising the importance of the irrigated sector of this industry. In these irrigated regions, there is continued pressure on the limited water resources available to the sugar industry as a result of competition with other crops and water users and frequent droughts. Surveys conducted amongst sugarcane farmers have indicated that there is a huge need for more information on techniques for maximizing efficiency in utilizing limited water resources and minimizing the loss of production associated with reduced water availability (Olivier and Singels, 2004). Despite a large number of available tools to assist producers with irrigation scheduling strategies (Culverwell *et al*., 1999), these are not widely used. Past research and practical experience worldwide have shown that tools for irrigation management on the farm should be simplistic and understandable if they are to be adopted by growers.

Maize is the staple diet of many South Africans and is extensively cultivated in SA. The estimated area under maize in 2012/2013 was 2.781 million ha, with 8.72% (242 500 ha) of this area under irrigation and the remainder under dryland production (Grain SA, 2013). The average maize yield under irrigation is 10.12 t/ha compared to 3.52 t/ha under dryland conditions. WUE of maize (defined here as kg grain/ha/mm ET) has increased over the past few decades and is affected by the cultivation method, stress experienced during production, weather and soil conditions and nutrient availability. Irrigation scheduling specifically can be an effective tool for improving the WUE of maize. Overall improvements in WUE in maize require the integration of measures that optimize cultivar selection and agronomic practices (Yada, 2011).

A number of data bases contain information of the WUE for specific agricultural crops (e.g. FAO, www.waterfootprint.org and the CAS data base) (Doorenbos and Kassam, 1979; Steduto *et al*., 2012; Sadras *et al*., 2013; Mekonnen *et al*., 2012; Hoekstra, 2013; Liu *et al*., 2007, www.waterfootprint.org). However, more frequent updates on or the near-real time estimates of WUE for a specific field or area is essential from improved crop production and water use management. With technological developments, it is now possible to estimate WUE over space and in time over the season. Satellite measurements can be utilized for the computation of biomass production, crop yield and actual evapotranspiration (ET). A number of examples exist of the use of these technologies to infer WUE from satellite data (Zwart *et al*., 2010; Klaasse *et al*., 2011; Jarmain *et al*., 2010).

While increasing WUE is promoted by water managers, farmers may have diverging short term views (Wichelns, 2014): farmers want to increase their returns and are not inclined to invest in water saving technologies and take risks on crop damage and production gaps due to insufficient water supply. Yet, improving WUE is a longer term necessity for sustainable farming. It is not unlikely that water licences will be based on efficient water usage in future and that WUE will become an ultimate indicator for the provision of legal water use licences. The best solution is to expose farmers to the newest technologies to measure WUE, let extension officers assist them with the interpretation of the data and convince them of the benefits.

In this project the accuracy of the remote sensing based technology for estimating WUE was investigated, but also ways for it to be adopted by users by illustrating data uses, transferring technology and building capacity. In that way, trying to develop the spatial technology to a point where it is more useable by farmers, extension officers, consultants and water managers. It is believed that the sugar and maize industries stand much to gain through improved water and production management as a result of the tools being developed in this project.

2. PROJECT OBJECTIVE AND AIMS

This project illustrated how spatially explicit information provided at frequent intervals can be used to determine, assess and potentially improve the WUE of irrigated crops.

Specific project aims include:

- Confirm the degree of accuracy ET, biomass, yield production and WUE estimated using the Surface Energy Balance Algorithm for Land (SEBAL) model (for selected crops and different spatial and temporal scales),
- Show how spatially explicit ET and yield data generated using the SEBAL model can be used by different users (researchers, farmers, irrigation advisors and boards, water users associations) to assess and improve the WUE at different spatial scales (field, farm or larger) and for selected irrigated crops,
- Develop spatial WUE information generated with the SEBAL model to the

point of operational use in South Africa and

- Build capacity (in students, researchers, extension officers, farmers, etc.) in the use of field and remote sensing based methods for improved WUE.

The accuracy of the SEBAL data sets was assessed (mainly) through comparison with other modeled and limited measured data sets.

3. ESTIMATING WATER USE EFFICIENCY

In order to address the set objective and aims, two economically important and high water using agricultural crops were selected: namely sugarcane and maize.

Study areas

Sugarcane study area: The sugarcane producing area around Malelane and Komatipoort represented the greater sugarcane study area. Sugarcane is exclusively produced under irrigation in this area. Thirteen sugarcane fields were selected for monitoring crop growth and soil water status in the field for which field specific information was known including cultivar, plant and harvest dates, irrigation system used and irrigation cycle. The original sugarcane study period (1 November 2011 to 31 October 2012) was extended to 31 July 2013 (30 November in certain instances), to cover a full (typical) sugarcane growing season better.

Maize study area: This study area covered an area of 60 km x 60 km around the town of Douglas, with extensive irrigated areas typically planted with maize in summer and wheat in winter in a dual cropping system. Numerous other summer crops are also grown under irrigation in this areas, but since maize is most extensively cultivated this crop was the focus of this study. Hence, a total of seven maize fields were monitored in this area in terms of crop growth, soil water and nitrogen status. Fields were studied over the period 1 October 2012 to 31 March 2013, extended to 31 May 2013. Most of the maize modelling and sampling was done between November 2012 and May 2013.

Field measurements

Field measurements related to crop development and the soil water balance (soil water content, rainfall, irrigation and evapotranspiration) were obtained in both study areas. Evapotranspiration was measured in one sugarcane and one maize field. Nitrogen data was collected in the maize fields only. Growth (e.g. canopy cover, leaf area index, destructively sampled biomass) was measured at roughly monthly intervals, except for crop yield determined only at the end of the growing season. Water balance measurements were made continuously or at weekly intervals. Evapotranspiration was measured continuously in sugarcane with the surface renewal system and in a maize field with a one sensor eddy covariance system. Nitrogen was also estimated in the laboratory from young, fully developed leaves collected over the season. Chlorophyll content in maize leaves was estimated using the spadometer at roughly monthly intervals.

Field scale modelling with MyCaneSim®

The MyCaneSim® system described by Singels (2007) and Singels and Smith (2006) consists of the CaneSim® sugarcane simulation model linked to an on-line weather and field database and an irrigation scheduling and advice module. It uses basic field data (e.g. soil water holding capacity, cropping details and irrigation system properties) to estimate the soil and crop status for each day of the growing season. The system is typically used to analyse agronomic performance of past seasons or predict water use, irrigation requirements and yields for the current season. In this project, the integration of near real-time field recordings of soil water content into MyCanesim® simulations was implemented. The system was used to simulate crop water use, growth and yield for all thirteen sugarcane fields studied using field specific soil and climate data.

Field scale modelling with the Soil water balance (SWB) model

The Soil Water Balance (SWB) model is a mechanistic, real time, generic, crop growth, soil water and nitrogen (N) balance and irrigation scheduling model (Annandale *et al.*, 1999, Singels *et al.*, 2010) and is based on the NEWSWB model from Campbell and Diaz (1988). SWB estimates crop growth and water balance fluxes using weather, crop and soil units. The big advantage of the SWB approach over crop factor based approaches is the feedback between water deficit conditions and the growth and development of the crop canopy. The N sub-model which estimates crop N demand, actual crop N uptake and other N fluxes as described in detail by Van der Laan (2009). SWB was set up for all seven maize field studied in this project using site specific information.

Crop water requirement modelling with SAPWAT

SAPWAT is a South African irrigation planning and management tool, based on CROPWAT (Smith, 1992) and commonly used to estimate crop water requirements. SAPWAT3 described by Van Heerden *et al*. (2008) was used in this study. SAPWAT utilises a four-stage crop development curve procedure, where the crop ET of a specific growth stage is estimated from reference evapotranspiration (ET_o) by applying crop specific coefficients. SAPWAT3 was set up for the selected sugarcane and maize fields using relevant soil depth, irrigation system, planting and harvesting dates and associated weather station data. In all the simulations, longterm daily average weather data was used to estimate ET for an optimally irrigated sugarcane and maize crop.

Spatial modelling with the Surface Energy Balance Algorithm for Land (SEBAL) and other spatial tools

The Surface Energy Balance Algorithm for Land (SEBAL) model was formulated by Bastiaanssen *et al*. (1998a, b). To estimate ET, SEBAL solves a set of equations in a strict hierarchical sequence to convert spectral radiances measured by satellites into estimates of the surface energy balance. Inputs on land characteristics and atmospheric properties such as the vegetation index, surface albedo, surface temperature and cloud cover are derived from satellite data. SEBAL requires spatially extrapolated meteorological data (wind speed, humidity and air temperature) from local weather stations and a digital elevation map (DEM). SEBAL provides spatial estimates of actual ET, crop potential ET, ET deficit, biomass production and biomass WUE, at pixel scale. SEBAL requires information captured in the visible, near-infrared and thermal infrared range of the electromagnetic spectrum. For the sugarcane modelling, data from the Disaster Monitoring Constellation (DMC) was combined with data from the MODerate Resolution Imaging Spectroradiometer (MODIS) satellite. For the maize modelling, DMC data was combined with data from the Visible Infrared Imaging Radiometer Suite (VIIRS). One set of satellite images per week was typically used in the modelling. Since the satellites capture data at different spatial resolutions, all data was rescaled to a 30m spatial resolution. Meteorological data from local weather stations were extrapolated for the respective areas. All the data products were available at weekly time steps.

A N tool developed by eLEAF was also applied in this project. This tool converts a chlorophyll index (derived from satellite data) into chlorophyll content and subsequently N content of the upper layers of the plant and for the entire canopy.

Freely available MOD16 ET data at $1km^2$ spatial resolution was also downloaded for the study areas and for the available periods.

Sugarcane yield modelling

The SEBAL model does not estimate yield, hence a new algorithm was developed to estimate cane and sucrose yield from the standard SEBAL outputs. Weekly biomass increments as estimated by SEBAL were partitioned into aerial dry mass and to stalks, following the approach used in the CaneSim® and Canegro models, fully described by Singels and Bezuidenhout (2002). Total biomass (TDM), aerial dry mass (ADM) and stalk dry mass (SDM) were calculated by accumulating weekly increments over time. Stalk fresh mass (an industry standard known as cane yield, CY) was calculated by dividing stalk dry mass by stalk dry matter content. The latter was calculated from stalk dry mass and sucrose mass following the method of Martine and Lebret (2001). The start of stalk growth was predicted by accumulating a specified amount of thermal time from the start of the crop (SEBALMC TT) or by predicting the start of stalk growth when SEBAL estimates of canopy cover reached 68 % (SEBALMC CC). The SEBAL spatial temperature and canopy cover data was used here.

The sucrose yield algorithm was conceived by Singels (2010) and is based on concepts published in Singels and Bezuidenhout (2002), Singels and Inman-Bamber (2011) and Singels *et al*. (2003). This model also used spatial SEBAL data sets.

Sugarcane yield forecasting

The CaneSim® crop forecasting system (CCFS) and daily data from approximately 70 weather and rainfall stations throughout the industry are used to simulate crops for each month of the milling season. Seasonal rainfall outlooks are used to generate 10 likely future daily weather sequences to simulate the future. Mean yields are calculated for homogenous climate zones, mill areas and the industry and expressed as a percentage of the yield of the previous year. This is done because simulated yields are always substantially higher than actual yields (Bezuidenhout and Singels, 2007b) because the model assumes ideal agronomic conditions including no limitations due to pests, diseases, weeds or nutrition. In this project the aim was to determine whether the accuracy of CaneSim® crop forecasts of irrigated sugarcane can be improved by using remotely sensed data to reset simulated data. The specific objectives were to compare virtual April and December forecasts of 2012 average yields for the two homogenous climate zones in the Komati mill supply area for each harvest month (April to December) with and without weekly SEBAL estimates of canopy cover (CC), actual evapotranspiration (ET), crop water status, biomass growth (ΔTDM) as model input, with actual yields. A virtual April forecast means that actual weather (and available SEBAL) data for the period from the start of the crop to 15 April are used as input, with likely future daily weather sequences used for the remainder of the growing season. A number of remotely sensed data variables were used to replace the CaneSim® simulated values, including canopy cover, daily transpiration, a soil water satisfaction index and the daily increment in total dry biomass.

Maize yield modelling

SEBAL does not produce estimates of grain yield, but only biomass production from which above ground dry matter and yield can be estimated. Dry grain yield was estimated by accumulating above ground dry matter from the date of flowering until harvest. Harvest indices, indicating the fraction of grain yield to above ground dry matter were also estimated using the SEBAL ADM data and the combine harvester measured yield.

4. RESEARCH FINDINGS

This project found that with the exception of a few data points, the SEBAL ET estimates typically exceeded the field observations slightly, but that the estimates were similar to that from the crop growth models evaluated. SEBAL ET for sugarcane was 1092±252mm/season. SEBAL ET for maize was 692±118 mm/season.

The SEBAL biomass production estimates, corrected to C4 ADM, agreed well with the observed estimates and typically exceeded the estimates from the crop growth models. SEBAL TDM for sugarcane was 47±19 t/ha and for maize it was 25±6 t/ha.

The SEBAL based yield estimates showed slightly different results for the two crops. For sugarcane weekly yield increments were estimated from weekly ADM increments after the estimated start of stalk growth. For growth, weekly yield increments were estimated from weekly ADM increments after the start of maize flowering. The SEBAL based yield estimates typically agreed better with final yield estimates at the mill (in the case of sugarcane) and the combine harvester data (in the case of maize). Cane yield recorded at the Malelane and Komatipoort mills in 2011/12 and 2012/13 ranged between 69 and 142 t/ha for the fields monitored in this study and the average yield calculated from the SEBAL data for a typical field was 80 t/ha. Combine harvester dry yield for six maize fields ranged between 9.9 and 14.1 t/ha.
Estimates of WUE, using spatial data sets were always found to be lower than when only data from the crop growth models were used. SEBAL WUE_{BIO} for sugarcane was 4.1±1 kg/m^3. SEBAL WUE_{SDM} was on average 1.94 to 3.4 kg/m^3 for the 13 field studied and for the entire study area (based on simulated yield and SEBAL ET) 2.70±0.46 kg/m^3. SEBAL WUE_{BIO} for maize was 3.5±0.5 kg/m^3 whereas the WUE_{GRAIN} ranged from 1.28 to 1.91 kg/m^3 for six fields studied. The large standard deviations suggest improvements in the WUE are possible.

Differences were found between the laboratory estimated N and spatial canopy N estimates, since (a) the laboratory analyses of N is based on samples from within a field, which could never be representative of an entire pixel or field, (b) the laboratory N estimates are calculated only for the youngest, fully developed leaves but (c) the canopy N represent the average N for a field, including the N percentage of not only young, but also old leaves.

SEBAL data have the potential to enhance weather-based crop model applications such as yield forecasting. Currently crop model-based forecasts use historic weather records to represent the recent past and expected future to simulate yield for a limited number of cropping scenarios (e.g. Bezuidenhout and Singels, 2007). Hence, forecasts have to rely on broad assumptions with regards to average soil and crop properties and irrigation practices for each scenario. SEBAL data could be used to (1) reset the current state of the crop (canopy cover, crop water relations, growth vigour, ADM) in model simulations and (2) introduce a finer resolution to yield forecasts, effectively increasing the number of scenarios and spatial variation, covered. This project has clearly shown that the quality of yield and production forecasts can be improved markedly by using SEBAL data as input into the CaneSim® Crop Forecasting System.

The main benefits which a technology that uses satellite data and a physically based algorithm like SEBAL brings to agricultural and water management, is the fact that (a) data can be represented spatially and (b) it is quantitative. Hence these spatial, quantitative data products can be used to evaluate farms and fields and to detect problems (anomalies) which can then be investigated further. Farmers can subsequently be advised in terms of, for example, better water management, based on trends in the data over space and time.

5. CAPACITY BUILDING AND TECHNOLOGY EXCHANGE

Students

Eight students from five Universities have been involved formally in this project: one PhD, three MSc, three BSc Hons and one BSc.

Two in-field training courses were presented as part of this project, to expose different students to the field technologies used to estimate WUE and evaluate the accuracy of the spatial technologies and estimates. Approximately 40 students were exposed to these methods during the training courses. The in-field training courses were presented by staff and researchers from the University of KwaZulu-Natal, University of Pretoria and South African Sugarcane Research Institute. A further two remote sensing focused training courses were held and a total of approximately 40 final year and post-graduate students exposed to the remote sensing technologies for WUE estimation. The training courses were presented by Prof Wim Bastiaanssen, with assistance from Dr Caren Jarmain.

The four training courses exposed students from five Universities and two research institutes to the new technologies: South African Sugarcane Research Institute, University of Pretoria, Stellenbosch University, University of KwaZulu-Natal, the University of the Free State, CSIR and the University of the Western Cape

Researchers

The project involved researchers from different Universities – University of KwaZulu-Natal, TU Delft, Stellenbosch University, University of Pretoria, University of the Free State and the SA Sugarcane Research Institute (SASRI). These researchers have skills in various fields. The researchers were exposed to different data sets, technologies and models through the project, whether through the training courses or just in working with the available data sets.

Technology transfer to farmers and industries involved in this project

The project technology partners, TSB and GWK as well as the farmers in their production areas have been exposed specifically to the spatial data sets through two web portals, SugarcaneLook and GrainLook. These web portals were greatly used to transfer knowledge to a range of users on new, frequently available, spatially explicit data products related to growth and water. The data available from these web portals formed the basis of discussions during many farmers and industry meetings listed below and were used extensively by TSB in farm evaluation and reporting. It can be concluded that, despite shortcomings with the web portals for data dissemination, or "data viewers" they served an important purpose of introducing users to the data sets and also in determining requirements of future dissemination tools.

6. PROJECT CONCLUSIONS AND EXTENT TO WHICH THE OBJECTIVES HAVE BEEN MET

In this section conclusions reached are related to the extent to which the objectives have been met.

It can be concluded that this project was successful in confirming that the degree of accuracy of data products from the Surface Energy Balance Algorithm for Land (SEBAL) model is acceptable for application in South Africa.

The accuracy of the SEBAL data products, ET, ET_{def}, CC, Biomass production and biomass water use efficiency, was tested extensively (for two important agricultural crops: sugarcane and maize, in 20 fields: representing a range of climatic, soils and agronomic conditions, over a period of 26 months: 18 months in sugarcane and eight months in maize, and against field observation and accepted South African crop growth and water balance models) and found to be acceptable.

The SEBAL data products were further developed for sugarcane yield estimation and yield forecasting. It can be concluded that these yield estimates and the forecasted cane yield is an improvement on the current method used. Also, that the yield estimates and forecasting can be further improved with frequent and consistent updates with the SEBAL data.

The SEBAL yield estimates can be improved for maize with the identification of the exact point of flowering. Also, the integration of SEBAL data sets into a crop forecasting system for maize can prove to be very beneficial.

The integration of field data (soil water content) into the web-based MyCaneSim® system, often used in decision support for operational irrigation management, improved the prediction of yields at field level when weather-based simulations are reset with soil water measurements.

It can be concluded that this project was successful in showing how spatially explicit data from the SEBAL model can be used by different users and for selected irrigated crops.

The SEBAL data provided through this project is quantitative and has a spatial dimension. It can be provided over an extensive area e.g. the entire Lowveld sugarcane production area, but with detail at a 30m spatial resolution. The quantitative spatial data has many uses for both the sugarcane and maize industry, specifically related to water management and yield estimation.

General farming practices can be evaluated in terms of ET, ETdef and WUE and recommendations derived, as was done by Dr Cronje (TSB).

For example, water management over an extensive area can be evaluated, but similarly on a field or farm level since the required detail also exists.

The ET_{def} data can be used effectively to define periods when improved water management is required, for example during periods of water stress or waterlogging. Similarly, poor water management can be identified by the WUE (biomass or yield related). Deriving benchmarking values is envisaged to prove useful for identifying problem areas.

It is further concluded that recommendations do not have to be based on a single measurement anymore (e.g. irrigation requirements of a crop) but can be derived from spatial data showing the area variation.

With the use of the spatial SEBAL data, sugarcane yield forecasting can be improved at mill level.

When combined with in-field observations, the impact of diseases or water stress on biomass production and crop yield can be evaluated.

It can be concluded that this project was successful in developing the SEBAL data products to the point of operational use in South Africa.

The spatial SEBAL data has been further developed through this project, to the point of operational application. The focus for operational application of the SEBAL spatial data has been on both yield estimation and forecasting and farming practice evaluation. The CaneSim® Crop forecasting system of SASRI has been developed to the point where SEBAL data, if available, can be used to improve yield forecasts at mill level. Further, the prototype data viewer developed by SQR software, integrating the SEBAL data into the CanePro data base, can effectively be used operationally to make evaluation of farming practices (irrigation, etc.) over different temporal and spatial scale more effective.

It is concluded that the fact that SEBAL data was available to the sugarcane industry to 18 months, greatly aided in the developed of the data to this point.

It is further concluded that for the SEBAL data to be operationally used for maize production, further exposure to the data and technology is required and hence further product development. The period of data exposure (eight months of data over a 12 month period) was too short. However, GWK is very open to the future use of SEBAL data, but specific products will have to be developed. For example a data viewer similar to that developed by SQRsoftware for viewing and evaluating farming practices, which can be integrated with the current GWK data base. There is also a need to derive benchmarking values from the SEBAL data, to make the application of data for irrigation scheduling and N management easier. A need further exists for integrating the SEBAL data into a model for crop forecasting.

It is concluded that technology adoption or the operational use of data takes time and that in this project this was mainly achieved in the sugarcane sector.

This project was successful in building capacity in the use of spatial and field based technologies, in researchers, students, farmers and industries.

This project allowed for general exposure of researchers to remote sensing SEBAL data products but also first-hand evaluation of the data and its accuracy. The integration of the spatial SEBAL data into a simplified version of the CaneSim® model for yield estimation and into the existing model for cane crop forecasting, proved that the accuracy and value of the spatial data was recognized by researchers and that the integration process improved the yield estimates and forecasts.

Researchers from institutions like South African Sugarcane Research Institute, University of Pretoria, Stellenbosch University, University of KwaZulu-Natal and the University of the Free State were exposed to the new technologies.

Four training courses were held, two in-field and two remote sensing application focused, which exposed a total of about 80 final year and post-graduate students. The project also produced an opportunity for students to engage in post graduate studies related to this project. This project exposed students from five universities and two research institutes to the new technologies: South African Sugarcane Research Institute, University of Pretoria, Stellenbosch University, University of KwaZulu-Natal, the University of the Free State, CSIR and the University of the Western Cape

Farmers producing sugarcane and maize within the study areas were exposed to the latest spatial technologies. Access to the data through the web-portals SugarcaneLook and GrainLook as well as meetings to discuss the data from individual fields and farms, facilitated this technology transfer and building of capacity in the use of this data. Over the three years tens of farmers were exposed in both study areas.

Technology transfer to our two industry partners in the project (TSB and GWK) was successful. This was illustrated in for example the active use of the SEBAL data disseminated through the SugarcaneLook webportal in farm evaluations and reports produced by Dr Cronje from TSB. A clear understanding of the use of the data was demonstrated and also the vision of integrating the data into existing platforms (CanePro) for future use.

7. ACKNOWLEDGEMENTS

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8. DATA

All processed data, including the SEBAL spatial data sets, have been stored at and can be obtained from the Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, Agriculture Faculty, University of KwaZulu-Natal, Carbis Road, Scottsville, Pietermaritzburg, 3209, South Africa.

9. PUBLICATIONS

Communicating information on and results from the project with farmers, researchers and other stakeholders were an important part of this project. This was done through a popular articles published, presentations at conferences and scientific articles published. These are listed below.

Popular articles

“Improved water use only a satellite away”, WaterWheel, September/October2011.
“New technology to estimate irrigation water use and sugarcane biomass production”, The Link, January 2012. http://www.sasa.org.za/TheLink.aspx.
“Water projek vir Suikerriet”, Spilpunt, May/June 2012. http://www.spilpunt.co.za/issu/spilpunt_may_june_2012/index.html.
‘Water use efficiency initiatives in the Onderberg’, SA Sugar Journal, April 2012.

Presentations at formal meetings and conferences

JARMAIN C. (2012a). ‘SugarcaneLook Improving water use efficiency’. South African Sugar Industry’s Agronomist’s Association’s Symposium – Technology for Agronomy, 25 October 2012 at Mt Edgecombe. (Invited talk)

JARMAIN C, SINGELS A, OBANDO-BASTIDAS E, OLIVIER FO and PARASKEVOPOULOS A (2012). Improving water use efficiency of sugarcane. Symposium of the South African National Committee on Irrigation and Drainage held from 20 to 23 November in Alpine Heath Resort, Drakensberg.

PARASKEVOPOULOS A, SINGELS A and VAN NIEKERK H (2012). Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. Symposium of the South African National Committee on Irrigation and Drainage held from 20 to 23 November in Alpine Heath Resort, Drakensberg.

SINGELS A, PARASKEVOPOULOS A and JARMAIN C (2013). Climate Change Impact on Productivity and Sustainability of irrigated Sugarcane Production: Exploring the use of Smarter Technologies for Improving Productivity and Water Use. Swaziland Sugar Conference Held at Ezulwini, Swaziland on 17 September 2013 (Invited talk).

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TAVERNA-TURISAN D (2013). Assessing the accuracy of the SEBAL model to estimate crop evapotranspiration, biomass accumulation and nitrogen status. University of Pretoria's Department of Plant Production and Soil Science Postgraduate Symposium, 29 August 2013.

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PARASKEVOPOULOS A and SINGELS A (2013). Integrating weather-based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. Proc. S. Afr. Sug. Technol. Ass. 86: 190-195.

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PARASKEVOPOULOS A.L. and SINGELS, A. 2014. Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. Computers and Electronics in Agriculture (Impact Factor: 1.77). 01/2014; 105:44–53.

BASTIDAS-OBANDO E, BASTIAANSSEN WGM and JARMAIN C (2014). Canopy resistance behaviour of rainfed and irrigated sugarcane described by leaf area index and environmental variables. Field Crops Research (In preparation).

List of completed Thesis

CLOETE C (2012). The use of remote sensing products for water use management in irrigated sugarcane crops in the Incomati river basin. Final Research Report submitted in partial fulfillment of the requirements for the degree Honours Baccalaureus (Geoinformatics), Stellenbosch University. 50 pages.

ESTERHUIZEN A (2012). Agriculture @ Android. Final Research Report submitted in partial fulfillment of the requirements for the degree Honours Baccalaureus (Computer Science), University of Stellenbosch, 18 pages.

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LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation / symbol	Unit	Name	Description
ε	g MJ-1	Light use efficiency	Total dry biomass produced per unit of photosynthetically active radiation (PAR) intercepted
ε_{max}	g MJ-1	Maximum Light use efficiency	A crop specific, maximum light use efficiency referring to the maximum amount of dry biomass produced per unit of PAR without reduction due to stress conditions
_24	W m-2	Daily average energy fluxes	
_i	W m-2	Instantaneous energy fluxes	
ΔADM	kg/ha/week	Weekly aerial dry biomass increments	
ΔS	mm per period	Change in soil water content	
ΔSDM	kg/ha/week	Weekly stalk dry biomass increments	Weekly increase in the dry mass of millable sugarcane stalks
ΔTDM	kg/week	Total Weekly biomass increments	Weekly total dry biomass increments
ΔTDM_{SEBAL}	kg/week	Total Weekly biomass increments based on SEBAL data	Weekly total dry biomass increments based on SEBAL data
ADL	mm	Allowable depletion level	The root zone available soil water content threshold for triggering a simulated irrigation in the MyCanesim® system
ADMPF	%	Aerial dry biomass partition fraction	Partition fraction of biomass increments to aerial biomass in sugarcane
$ADMPF_{max}$	%	Maximum aerial dry biomass partition fraction	Maximum partition fraction of biomass increments to aerial biomass in a mature sugarcane crop
Alpha		Alpha weighting factor	Regression coefficient fit when Surface renewal sensible heat flux (H) is compared against an independent measure of H such as Eddy Covariance
ARC		Agricultural Research Council	
ASWC	mm	Available soil water content	Plant available soil water content of the rootzone
B		ADM partitioning extinction coefficient	Empirical sugarcane biomass partitioning parameter
Bio	kg/ha/period	Biomass production	
C3, C4 crops		Carbon fixation plants using the C3 and C4 pathways	Crops with different metabolic pathways for carbon fixation in photosynthesis
CC	% or fraction	Canopy cover	Proportion of ground covered by green foliage
CCFS		Canesim® crop forecasting system	A model based system for forecasting sugarcane yields
$CCFS_{ET}$		Canesim® crop forecasting system driven mainly by transpiration	
$CCFS_{RAD}$		Canesim® crop forecasting system mainly driven by	

Abbreviation / symbol	Unit	Name	Description
		intercepted radiation and water status	
CC_{SEBAL}	%	Canopy cover estimated from SEBAL data	The fraction of ground area covered by green sugarcane leaves as estimated from SEBAL data
CC_{skp}	%	Canopy cover at the start of stalk elongation	The fraction of ground area covered by green sugarcane leaves at the start of stalk elongation
CR	mm or %	Soil water conversion ratio used to convert the SWI to ASWC	Conversion ratio defined as the amount of ASWC per unit of SWI.
CR	mm per period	Capillary rise of water in the root zone	
CY	t/ha	Cane yield	The fresh (containing typically about 75% water) mass of millable sugarcane stalks.
DAP	Day	Days After Planting	
DEM	m	Digital Elevation Map	A map showing elevation
DMC		Disaster Monitoring Constellation	Satellite sensor acquiring data at 22m resolution within the visual and near-infra red spectral ranges
DP	mm per period	Deep percolation	
EF	Unitless	Evaporative fraction	Describing the ratio of the latent energy flux density to the available energy (Rn-G)
ET	mm per period	Evapotranspiration	Evapotranspiration from a vegetated surface, consisting of transpiration from the green canopy, evaporation from the soil surface and evaporation of intercepted water
Etd_{ef}, $ET_{defSEBAL}$	mm per period	Evapotranspiration deficit	Difference between actual and potential evapotranspiration estimated by SEBAL
ET_o	mm per period	Reference evapotranspiration	Evapotranspiration from a reference surface, typically a short well-watered grass surface experiencing no water or nutrient stress
ET_{SEBAL}	mm per period	Evapotranspiration estimated with SEBAL	
FC_{SWI}	%	Soil water index at field capacity	The reading from a capacitance probe when the soil water content is at field capacity or the drained upper limit.
FI	%	Fractional interception of PAR	The fraction of incoming PAR that is intercepted by the green canopy
Field values		Data values measured in the field	
G	W m-2	Soil heat flux density	Energy heating the soil surface
H	W m-2	Sensible heat flux density	Energy heating the atmosphere and sensed
HI	Unitless	Harvest index	Index relating crop grain yield to total above ground dry matter production
I	mm per period	Irrigation	
Intercept		Y intercept of the linear curve fitted to a data set	The intercept of the fitted line is such that it passes through the center of the data points.
INTgreen		Number of elongating internodes	Assumed number of elongating, green sugarcane internodes at any time

Abbreviation / symbol	Unit	Name	Description
Irrig		Irrigation type	
Irrig. amnt	mm	Irrigation amount	The assumed irrigation amount applied per event, from original design specifications
k_c	Unitless	Crop factor	Factor relating the actual to reference evapotranspiration
k_cET(new)	mm per period	Evapotranspiration estimates used by GWK	Evapotranspiration estimates used by GWK and based on recent kc values published by Snyman (2011)
k_cET(old)	mm per period	Evapotranspiration estimates used by GWK	Evapotranspiration estimates used by GWK and based on old kc values
LE	W m-2	Latent energy flux density	Energy driving evaporation and transpiration processes
MGB		Mill Group Board	
MOD12Q1 MOD12		MODIS global landcover product	Land cover data generated from MODIS satellite data
MOD13A2	Unitless	MODIS Enhanced Vegetation Index product	Enhanced vegetation index from MODIS satellite data
MOD15A2	Unitless	MODIS Leaf area index product	Leaf area index estimated from MODIS satellite data
MOD16	mm per period	MODIS Evapotranspiration product	Evapotranspiration from MODIS satellite data
MOD43C1		MODIS surface reflectance product	Reflectance data generated from MODIS satellite data
MODIS		MODerate resolution Imaging Spectroradiometer	Satellite sensor acquiring data at varying spatial resolution (250 to 1000m) for a range of spectral bands (visual, near-infra red, thermal infrared)
MPCGA		Mpumalanga Cane Growers Association	
N		Nitrogen	
n		Number of data pairs	Number of records or data points considered in statistical analysis
NDVI	Unitless (µm µm-1)	Normalised Difference Vegetation Index	Ratio of the difference of NIR and R and the sum of NIR and R and Indicating whether a surface sensed contains actively growing vegetation.
NIR	µm	Near Infra-red	Spectral reflectance within the near infra-red spectral band
NOAA		National Oceanographic and Atmospheric Administration	
NWM		Neutron water meter	Sensor estimating water content
Obs	t ha-1	Observed (measured) yield estimates (cane, sucrose)	
Obs	%	Observed (measured) sucrose content	
OH		Overhead irrigation - centre pivot or dragline	
OPEC		Open Path Eddy Covariance System	
P	mm per period	Precipitation	
p		Statistical significance factor	
PAR	µmol photons	Photosynthetically Active	Solar radiation within the spectral range

Abbreviation / symbol	Unit	Name	Description
	m-2 s-1; or Wm-2	Radiation	of 400 to 700 nm, used in the process of photosynthesis (corresponding approximately with the range of light visible to the human eye).
PET	mm per period	Potential evapotranspiration	Evapotranspiration rate of a well-watered crop with partial or full canopy cover.
R	µm	Red	Spectral reflectance within the red spectral band
R	mm per period	Runoff	
R^2		Statistical coefficient of determination	Statistical indicator of wellness of fit of a statistical model (curve or line) to a set of data points
R_n	W m-2	Net radiation	The difference between (incoming and outgoing short and long wave radiation above a vegetated surface.
r_s	s m-1	Bulk surface resistance	Resistance to vapour flow through the transpiring crop and evaporating soil surface
RS		Remote sensing	
RVI		Relative value index	Index representing the favourability of temperature and water status conditions during the last four weeks for sucrose accumulation in the sugarcane stalk
SAPWAT			Irrigation planning and management model / tool (developed by Van Heerden, 2008)
SD		Surface drip irrigation	
SDM	kg/ha or t/ha	Stalk dry mass	The dry mass of millable sugarcane cane stalk per unit ground area
SDM	kg/ha or t/ha	Stalk dry mass	The dry mass of millable sugarcane cane stalk per unit ground area
SEBAL		Surface Energy Balance Algorithm for Land	Energy balance model utilizing remote sensing data (developed by Bastiaanssen, 1998) and estimating ET and biomass production
SEBALMC CC		SEBAL sugarcane yield model	Sugarcane yield model combining SEBAL data with MyCanesim theory, with CC to initiate stalk growth
SEBALMC TT		SEBAL sugarcane yield model	Sugarcane yield model combining SEBAL data with MyCanesim theory, with thermal time to initiate stalk growth.
SKPF		Stalk partition factor	Partition fraction of dry biomass increments to stalk mass and dependent on the development phase of the crop
Slope		Slope of the linear curve fitted to a data set	The slope is equal to the correlation between data points on the y and x axis, but corrected by the ratio of standard deviations of these variables
SRTM		Shuttle Radar Topography Mission	Sensor used to determine DEM
SSD		Sub-surface drip irrigation	
Stdev		Standard deviation	
SUC_{max}		Maximum stalk sucrose content	Sucrose content (dry mass basis) assumed for the ripened section of a hypothetical

Abbreviation / symbol	Unit	Name	Description
			stalk of a mature sugarcane crop
SWB		Soil Water Balance	Model for crop growth and soil water balance and irrigation scheduling
SWB-Pro		Soil Water Balance irrigation scheduling programme	
SWB-Sci		Soil Water Balance model research version	
SWI	%	Soil water index	Soil water index reading of the soil capacitance probes, ranging between 0% for air and 100% for water
SWSI		Soil water satisfaction index	An index to quantify crop water status (1 implies no water stress, 0 implies fully water stressed)
SY	t ha-1	Sucrose yield	The mass of sucrose in harvested cane stalks per unit ground area
T	^{o}C	Air Temperature	
T	mm	Transpiration	
TAM	mm	Total Available Moisture	The amount of water in the root zone available to the plant when the soil profile is at field capacity
TT	^{o}C.d	Thermal time	Effective daily temperature above a given base temperature, accumulated over a given period.
TTemerge	^{o}C.d	Thermal time required for primary shoot emergence	Thermal time from the start of a ratoon crop to the emergence of primary shoots
TTint	^{o}C.d	Thermal time requirement for the appearance of internodes	Thermal time required to produce an internode after the first internode
TTint1	^{o}C.d	Thermal time required to produce the first internode	Thermal time required to produce the first internode after shoot emergence
TTskp	^{o}C.d	Thermal time requirement for the start of stalk growth	Thermal time from shoot emergence to the start of stalk growth
VIIRS		Visible Infrared Imaging Radiometer Suite	Satellite sensor
WUE_{BIO}	kg m-3	Water use efficiency calculated from biomass production	Amount of total dry biomass produced per unit of evapotranspiration
WUE_{GRAIN}	kg m-3	Water use efficiency of grain	Water use efficiency defined as the dry grain produced per unit of evapotranspiration
WUE_{SDM}	kg m-3	Water use efficiency calculated from stalk dry mass	Amount of stalk dry mass produced per unit of evapotranspiration
$Yield_{GRAIN1}$	t ha-1	Crop Grain yield based on a harvest index	Crop Grain yield estimated from a Harvest index and the total above ground dry matter production
$Yield_{GRAIN2}$	t ha-1	Crop Grain yield based on period accumulated ADM	Crop Grain yield estimated from accumulated Above dry matter production between the period flowering and harvest
Y_{IRR}	t ha-1	Simulated cane yield using inferred irrigation.	MyCanesim® simulated cane yield using inferred Irrigation
Y_{opt}	t ha-1	Simulated cane yield using optimal irrigation.	MyCanesim® simulated cane yield using an optimal irrigation schedule.

Abbreviation / symbol	Unit	Name	Description
Y_{swc}	t ha-1	Simulated cane yield using corrected available soil water Content	MyCanesim® simulated yield, using measured soil water recordings to correct simulated soil water.

DEFINITION OF KEY TERMS

ADM	Aerial Dry Matter or above ground biomass production is defined as the dry mass of above ground plant material per unit ground area.
Albedo	Albedo (reflection coefficient) is a measure of the reflectivity of the earth's surface. Albedo is the reflected light, defined as the ratio of reflected to incident radiation.
Biomass from observations	Field observations refer to total above ground dry matter (ADM) at the time of sampling, in kg/ha
Biomass in CaneSim®	CaneSim® estimates above ground dry matter (ADM) and total dry matter content (TDM) in kg/ha
Biomass in SEBAL	The biomass production in SEBAL refers to total dry matter (TDM) which includes above plus below ground dry matter production. SEBAL typically estimates biomass at intervals – in this project at weekly intervals (kg/ha/wk)
Biomass in SWB	Biomass in SWB refers to the above ground biomass production in kg/ha
Biomass water use efficiency or WUE_{BIO}	Total biomass produced (kg/ha) per unit of water used (SEBAL estimated ET) (mm)
Canopy cover or CC	Canopy cover can be defined as the proportion of soil covered by the canopy The canopy cover is an indicator of development of the crop during the growing season
Evapotranspiration deficit or ET_{def}	SEBAL estimates an evapotranspiration deficit (ET_{def}) as the difference between the potential and actual evapotranspiration Indicator of plant (water) stress Expressed in mm/week
Evapotranspiration or ET from SAPWAT	Crop evapotranspiration (ET) of a specific growth stage is related to short grass reference evapotranspiration (or ET_o) by applying a crop coefficient
Evapotranspiration or ET from SEBAL	In SEBAL actual evapotranspiration (ET) is equivalent to the latent energy flux density (a component of the energy balance) and refers to the actual total evaporation and transpiration from a surface
Evapotranspiration or ET from SWB, CaneSim®	Evapotranspiration (ET) refers to the total evaporation and transpiration modeled with the respective models
Harvest index	An index representing the grain yield from aerial dry matter
Irrigation efficiency	The classical Irrigation Efficiency (IE) describes which portion of the water withdrawn from the source or applied at the farm gate, is available for root water uptake
k_c	Crop factor relating actual and reference evapotranspiration
Leaf N percentage	Leaf N (%) was estimated from the N in the leaves divided by the estimated dry matter of the leaves.
Normalised Difference Vegetation Index or NDVI	Normalised Difference Vegetation Index provides an indication of the growth vigour of a crop or vegetation. NDVI is calculated as the ratio of the difference in the spectral reflectance measurements acquired in the near infra-red (NIR) and red (R) range, to the sum of the Near Infra-red and red spectral reflectance estimates

Potential evapotranspiration (PET)	SEBAL estimates in addition to the actual evapotranspiration, the crop potential evapotranspiration. The potential evapotranspiration represent crop specific evapotranspiration under conditions of no stress (water or nutrient).
Potential evapotranspiration or PET	The amount of water that could be evaporated and transpired if sufficient water was available
Reference evapotranspiration or ET_o	Evapotranspiration from a short grass, reference crop experiencing no water or nutrient stress
TDM	Total dry biomass refers to the dry mass of above and below parts of the plant per unit ground area (above ground plus below ground biomass)
Upper leaf N and total N in the canopy	N in the upper leaves of the canopy is estimated from the chlorophyll index estimated from satellite data. Total N in the canopy is estimated from the upper leaf N and the leaf area index. Both estimates are in kg/ha.
Water use efficiency of grain or WUE_{GRAIN}	Water use efficiency based on grain yield and SEBAL ET estimates
Water use efficiency of sugarcane or WUE_{SDM}	Stalk dry mass (SDM) (yield) (kg/ha) produced per unit of water used (mm)
Water Use Efficiency or WUE	Water Use Efficiency (WUE) intends to describe the crop production (either harvestable yield or Above dry matter produced) per unit of water consumed or lost through evapotranspiration
Yield in maize	
▪ Sucrose content	Stalk sucrose content (dry mass basis) is derived by dividing sucrose mass by stalk dry mass
▪ Stalk dry matter / mass	Dry mass of millable stalk per unit area
▪ Stalk dry matter content	Stalk dry matter content was determined by drying stalks and weighing them before and after drying. Stalk dry mass is then calculated by multiplying the stalk fresh mass with stalk dry matter content.
▪ Optimum	Optimum yield refers to yield without any stress conditions for the specific irrigation system
▪ Observed yield	Cane yield was determined through destructive sampling in t/ha. The field average cane yield was also determined by the mill in t/ha.
Yield in sugarcane	
▪ Total harvestable yield (for SWB, field observations)	Yield of maize in SWB refers to the total harvestable yield (t/ha) and include both grain and cob mass
▪ Grain yield (SEBAL)	SEBAL estimated grain yield (t/ha) is derived from above ground dry matter (ADM) increments and only includes the grain
▪ Combine harvester yield	A modern combine harvester record grain yield (t/ha) in yield maps at the moisture content at harvest time In this project the yield data was corrected to 0 % moisture

CHAPTER 1: INTRODUCTION

By Caren Jarmain, Wim Bastiaanssen, Francois Olivier and Michael van der Laan

1.1 GENERAL INTRODUCTION

The need for increased food and timber production due to population increases and economic development has led to dramatic increases in land under irrigated agriculture and forestry in South Africa (SA). Consequently, increased competition for water between different users (agriculture and forestry, industries, municipalities / urban sector) is urging regulators of water supplies to find solutions and / or interventions to alleviate this growing pressure on water of a sufficient quality and quantity. This situation is exacerbated by the reality of climate change and the concurrent predictions of worsened future water availability scenarios. South Africa, as a largely semi-arid country (MAP of 475mm), is particularly vulnerable. In 2000 it was reported that 12 of the 19 catchments in SA experienced water deficits, which were partly offset by inter-catchment water transfer schemes (Blignaut *et al*., 2009). Under current development trajectories, SA is expected to experience particularly severe water shortages in the future. In addition, compliance with relevant legislation embodied in the National Water Act (DWAF, 1998) and the meeting of international trans-boundary water supply obligations are mandatory. Interventions to augment water availability (desalinisation of sea-water, water-transfer schemes) are immediate engineering solutions, but have limited scope to address the problem in its entirety and are prohibitively expensive. Hence, the construction of additional large storage dams is no longer a viable option in South Africa. The longer-term solution and intervention lies in understanding how, and improving the efficiency with which water is used, reducing wastage and ensuring that unnecessary "water exports" are avoided.

A good understanding of the water use of the major land uses is key to assessing and improving the efficient use of water, as well as for integrated water resource management, specifically within the context of the National Water Act (1998) (DWAF, 1998) which clearly states that water should be used efficiently. This is particularly relevant for irrigated agriculture in SA where an estimated 1 675 882 ha is registered for irrigation use (Van der Stoep *et al*., 2008). It is estimated that irrigated agriculture uses between 59 (Backeberg, 2005) and 63 % (Water Accounts for South Africa, 2000 in WWF and Reinders, 2010) of South Africa's water resources.

1.2 MOTIVATION FOR SPATIAL METHODOLOGY

Numerous methods available locally and internationally are used to provide farmers, irrigation boards (IB) and Water Users Associations (WUA) with information on crop water use (or water losses through the processes of evapotranspiration, ET), crop irrigation requirements, biomass and yield production and efficiency with which crops area produced or water use efficiency (WUE). Field based methods (e.g. lysimeters, Eddy covariance, Bowen Ratio, surface renewal, scintillometry, soil water balance) used to estimate (or measure) evapotranspiration (ET) from surfaces have been evaluated in various Water Research Commission (WRC) funded projects (see Bristow and De Jager, 1981; Green and Clothier, 1988; Olbrich, 1994; Dye *et al*., 1997; Savage *et al*., 1997, Everson *et al*., 1998; Everson, 1999; Savage *et al*., 2004; Jarmain *et al*., 2009a). Numerous models have also been developed in SA (e.g. SWB, SAPWAT, BEWAB, CANESIM®) to estimate crop water use and crop irrigation water requirements from agricultural fields and these have also been evaluated in past WRC funded projects (see Bennie *et al*., 1998; Annandale *et al*., 2005; Ehlers *et al*., 2007; Bezuidenhout and Singels, 2007 a,b; Van Heerden *et al*., 2008). These methods however have limitations: (1) they do not provide a spatial presentation of patterns or variations in e.g. crop water use across and in between agricultural fields or a region; and (2) most of these methods are not applied operationally to assist farmers and other users (IB or WUA) with agricultural water management.

Advances in recent years in the use of remote sensing (RS) information makes it now possible to assess crop water use, biomass and yield production (and WUE) spatially for each pixel (< 30 to 1000 m) of a satellite image. Spatially explicit methods have the potential to contribute greatly towards improved water management at field, farm or even larger scales. Different methods have been developed to provide information at a range of temporal and spatial scales and for various applications. For agricultural (field scale) applications a number of models have been developed, including the Surface Energy Balance Algorithm for Land (SEBAL) model, Surface Energy Balance System (SEBS) model, Mapping EvapoTranspiration with high Resolution and Internalised Calibration (METRIC^{tm}) model, Vegetation Index / Temperature Trapezoid (VITT) model, Two Source Energy Balance (TSEB) model, the Atmosphere-Land Exchange Inverse (ALEXI) model, NDVI-DSTV (Normalised Difference Vegetation Index Diurnal surface temperature variation) triangle model, and others. Many of these methods estimate ET as the residual of the shortened energy balance equation and hence require surface temperature estimates, whilst others use a WUE relationship to determine ET.

The SEBAL and the METRIC^{tm} models are used operationally for field scale agricultural water management (e.g. www.mijnakker.nl, fruitlook.co.za; http://www.idwr.idaho.gov/GeographicInfo/METRIC/et.htm), whilst most others are used mainly in research applications. A selection of the models was reviewed by Jarmain *et al*., (2009b) for their accuracy in estimating ET and also their potential for operational applications in SA. Numerous other publications have also reviewed these models ito their accuracy and application (see Norman *et al*., 1995; Zhan *et al*., 1996; Bastiaanssen *et al*., 1998 a, b; Kite and Droogers, 2000; Courault *et al*, 2005; Timmermans *et al*., 2005; Bashir *et al*., 2006; Timmermans *et al*., 2007; Marx *et al*., 2008; Sanchez *et al*., 2008; Su (undated); Gibson *et al*., 2013).

Numerous other RS based models have been developed and provide ET estimates at lower spatial resolutions (often ~1 to 3 km), but higher temporal resolutions (30 min. to daily). The lower spatial resolution of these models makes them less suited for agricultural applications, where information at field scale is required. A number of these models use Meteosat Second Generation (MSG) satellite data and provide ET data at 30 min. intervals, at a resolution of 1-3 km resolution (see http://landsaf.meteo.pt/; see also EARS at http://www.ears.nl/). ET data from HYLARSMET (see http://sahg.ukzn.ac.za/soil_moisture/et/) is also estimated daily and similarly, ET from a MODIS is estimated daily for the entire globe at a 1 km resolution (see http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=16). The Global water cycle monitor from Princeton University also estimates ET at a daily time step (see http://hydrology.princeton.edu/~justin/research/project_global_monitor/). The ALEXI model can also be used to estimate energy fluxes and other parameters daily, e.g. at a 10 km spatial resolution (see http://alfi.soils.wisc.edu/cgi-bin/anderson/alexi_server.pl?region=SMEX02MOD).

The SEBAL model is used to estimate ET (mm), biomass production (from which crop yield, in kg, is determined empirically) and WUE (defined at yield production per unit water used, in kg/m3) typically at a weekly time step and for each pixel of a satellite image at spatial scales of <30 to 250 m. Assessing the spatial WUE data over time can help farmers to detect e.g. an uneven application of irrigation water (in a field or across a farm or irrigations scheme), a mismatch between irrigation water supply and that actually required (indicating over- or under-irrigation), potential seepage losses or drainage problems and other resources (e.g. fertilizer and energy) wastage. If problems are detected and addressed promptly, farmers and irrigated agriculture in general, can potentially save substantial amounts of water, and actively improve the efficiency with which water is used and crops are produced by this sector. In certain countries, the spatial data is already being used operationally for on farm management. Since 2007 the 'BoerInBeeld' project has used SEBAL WUE data to assist precision farming in the Netherlands. In 2008, this operational product was transformed into 'FieldLook' (www.fieldlook.com) with numerous farmers using this product. Since 2011, the 'FruitLook' project also provides deciduous fruit producers in the

Western Cape Province of South Africa with spatial SEBAL data. These web-based products allow reviewing weekly updates on e.g. crop water requirements, crop water use, biomass production and nitrogen levels which can assist farmers and advisors in management decisions relating to water and fertilizer applications.

South Africa has progressed much in research related to applying and evaluating remote sensing derived data from SEBAL for improved water management (e.g. Klaasse *et al*, 2008; Jarmain, *et al*., 2009b, Jarmain *et al*., 2010; Meijninger and Jarmain, 2014; CSIR, 2012; Klaasse and Jarmain, 2012). There is now a need for this type of information to be made available so it can be used operationally. SEBAL has shown great potential in past projects where crop WUE was evaluated (Klaasse *et al*, 2008; Jarmain, *et al*., 2009b, Jarmain *et al*., 2010; ; CSIR, 2012) and it is already operationally used internationally and in support of irrigated agriculture, whilst continually being improved through research. Much confidence exist in this model and it potential uses.

1.3 IMPORTANCE OF AGRICULTURE IN SOUTH AFRICA

The agricultural sector remains economically important since it contributes to product exports, employment, livelihoods and food security. The production of maize and sugarcane remains two important crop industries in South Africa. Both of these crops are seen as high water users. In the production of these important crops, much information is needed. Farmers require accurate information on crop water use and yield at (and across) field scale and on farm level, so they can assess their use of water, reduce wastage and optimize crop production and fertilizer use. Irrigation Boards and Water Use Associations require information on crop water use across their management areas, so actual irrigation water requirements e.g. for requesting water releases from upstream reservoirs, can be determined more accurately. Government departments like Department of Water Affairs (DWA) need to accurately assess irrigation water required (in a catchment) for planning purposes, so trans-boundary obligation can be met.

1.3.1 Importance of irrigated sugarcane in South Africa

The South African sugar industry makes an important contribution to the national economy, through its agricultural and industrial investments, foreign exchange earnings, high employment rate and its linkages with suppliers, support industries and customers. Sugarcane is grown on approximately 380 000 ha, extending from Northern Pondoland in the Eastern Cape Province through the coastal belt and KwaZulu-Natal Midlands to the Mpumalanga Lowveld. The industry produced 20 million tons of sugarcane and 2.35 million tons of sugar in 2013 (Singels *et al*., 2014). The majority of the area under sugarcane relies on rainfall and only 24% of the area under cane is irrigated. Sugarcane produced in the Mpumalanga (Komatipoort and Malelane) and Pongola regions are done so exclusively under irrigation. This area represent 16% of the total area under sugarcane but produces almost 30% of the total annual sugarcane crop emphasising the importance of the irrigated sector of the industry (South African Cane Growers Association, 2013, personal communication).

In the irrigated areas like the Mpumalanga region, there is continued pressure on the limited water resources available to the sugar industry through competition with other crops and water users and frequent droughts. In addition, water use for agriculture is subject to increasing scrutiny from policy makers and environmentalists with the result that the industry is under increasing pressure to demonstrate that water is being used efficiently.

The term ‘water use efficiency’ (WUE) is widely accepted in the sugarcane sector as a measure of overall effectiveness of water use (either rainfall, or irrigation, or both) for crop production. A distinction can be made between WUE, which can be defined as cane yield per unit of total crop water use (evapotranspiration) and irrigation water use efficiency (IWUE), which can be defined as the cane yield response per unit of irrigation water applied (Inman-Bamber *et al*., 1999).

Low IWUE has been identified as a major problem in the northern Mpumalanga irrigated areas in spite of a very high climatic potential (Olivier *et al*., 2009). The average IWUE in the Onderberg is approximately 6 t cane per 100 mm irrigation water applied (Olivier and Singels, 2003). Many published responses to irrigation are in the 6 to 12 t cane per 100 mm range (Thompson, 1976; Kingston, 1994; Inman-Bamber *et al*., 1999), but higher values of 22 to 48 t sugarcane per 100 mm have been reported (Robertson and Muchow 1994; Robertson *et al*., 1997; Inman-Bamber *et al*., 1999) depending on the irrigation scheduling strategy, seasonal rainfall and stage of crop development.

Surveys conducted amongst sugarcane farmers (Olivier and Singels, 2004) have also indicated that there is a huge need for more information on techniques for maximizing efficiency in utilizing limited water resources and minimizing the loss of production associated with reduced water availability. Agronomic practices such as the use of a trash blanket, reduced row spacing, growing suitable varieties and accurate irrigation scheduling could be applied successfully to increase IWUE by saving water and/or increasing yield. For example, research work carried out in various sugarcane areas of the world has shown that the retention of a trash blanket following green cane harvesting can have considerable yield responses in lower rainfall areas and little or negative responses in super-humid and low-temperature areas (de Beer *et al*., 1996). Thompson (1976) reported average cane yield responses of 10 t ha^{-1} per annum under rain-fed conditions but under irrigation the response to trash retention was much lower. However, some negative responses to trash blanket systems have also been observed with regards to insect pests such as trash worm and Eldana (de Beer *et al*., 1996). These negative effects may vary according to the variety, season of harvest and amount of trash material present. Despite early claims of large yield increases from high plant population densities in narrow rows to achieve more rapid tiller and leaf area development (Bull and Bull, 1996, 2000), subsequent results of independent trials and commercial evaluations have been disappointing (Garside *et al*., 2002). The advantage of increased interception and cane yield at high plant densities usually diminishes with crop and ratoon age (Singels *et al*., 2005 a).

According to Singels *et al*. (2005 b) there is some opportunity for increasing sugarcane productivity by correctly matching variety to the environment and managing them correctly. Specific varietal characteristics will play a key role in determining the response to a trash blanket and high planting density production system.

Also, despite a large number of available tools to assist producers with irrigation scheduling strategies (Culverwell *et al*., 1999), ranging from relatively simple instruments to measure soil water content directly, to sophisticated crop models that estimate the soil water content through water budgeting (Olivier and Singels, 2004), these are not widely used. The tools are either perceived as too complex and difficult to use (Olivier and Singels, 2004), or growers, in particular small scale and emergent farmers, simply do not have easy access to such technologies. Past research and practical experience worldwide have shown that tools for irrigation management practices on the farm should be simplistic and understandable if they are to be adopted by growers. Reported values of IWUE are traditionally low in the irrigated areas of the sugar industry and as a result the industry is under increasing pressure to demonstrate that water is being used efficiently. It is therefore believed that that the sugar industry stands much to gain through improved irrigation scheduling practice as a result of the tools being developed in this project.

1.3.2 Importance of irrigated maize in South Africa

Maize is the staple diet of South African people and is produced in all nine provinces. According to Grain SA (2013), the estimated area under maize in 2012/2013 was 2.781 million ha, with 8.72% (242 500 ha) of the area under irrigation and the rest under dryland production. DAFF (2013) estimated the area under maize at 3.141, 2.859 and 3.262 million ha for 2011/2012, 2010/2011 and 2009/2010, respectively. The average maize yield under irrigation is 10.12 t/ha and 3.52 t/ha under dryland conditions. Even though irrigated maize only covers a small area, it contributes an estimated 21.5% of the total maize production of South Africa. The gross value of maize production in 2011/2012 was estimated at R24.512 billion. Approximately 9000 commercial famers produce maize in South Africa, providing employment to an estimated 128 000 people (www.daff.gov.za.innopac.up.ac.za/docs/FactSheet/maize.htm, accessed 26 March 2014).

The WUE of maize (defined here as kg grain/ha/mm ET) has increased over the past few decades. Bennie and Botha (1986) reported WUEs of 10.8-12.2 kg grain/ha/mm, depending on cultivation method. From trials conducted in the USA in 1994 and 1995, Tolk *et al*. (1999) reported WUEs ranging from 12.6-15.8 kg grain/ha/mm. In a season with high evaporative demand, the authors observed that a mulch layer resulted in a 17% increase in grain yield and a 14% increase in WUE compared to bare soil. Using measured data from a 30 year experiment in the North China Plain, Zhang *et al*. (2011) showed that while ET_o remained relatively constant between 1979 and 2009, seasonal ET of maize gradually increased. The authors attribute this to higher leaf stomatal conductance in the newer cultivars. As increases in grain yield were relatively larger than increase it ET, Zhang *et al*. (2011) further concluded that new cultivars and improved management could lead to higher production 'without much increase in water use'. Grain yield reduction due to water stress can be as much as 25% prior to silking[1], 50% at silking and 21% after silking (Denmead and Shaw, 1960). Hatfield *et al*. (2001) reviewed WUEs for maize produced in a variety of cropping system research trials comparing different management practices. A very wide range of WUEs of 2.4 to 18.9 kg grain/ha/mm were observed. It was noted that WUE can vary two-fold within a field due to soil type differences. Hatfield *et al*. (2001) concluded that WUE can be increased by 25 to 40% through tillage management practices and by 15 to 25% by modifying nutrient management practices. Irrigation scheduling can also be an effective technique for improving the WUE of maize. Overall, improvements in WUE in maize require the integration of measures that optimize cultivar selection and agronomic practices (Yada, 2011). It is believed that maize producers will potentially benefit greatly from the tools developed in this project, identifying problems in their agronomic practices.

1.4 TECHNOLOGICAL ADVANCES IN ESTIMATING WATER USE EFFICIENCY IN AGRICULTURE

In the beginning of the 20th century agricultural scientists from the United States started to look at the relationship between water use and dry matter production. Calculation of evapotranspiration in field experiments proved to be quite unreliable since certain components of the water balance could not be determined at all, or could only be estimated roughly. Most experiments at that time were conducted in pots, and by covering the soil surface, transpiration could be determined with greater certainty. Pioneering work was conducted by Briggs and Shantz (1913) who determined for lucerne a transpiration ratio, defined as the amount of water required to grow a certain dry weight of crop. One of the conclusions drawn by many and summarized by De Wit (1958), based on a synthesis of experimental results, was that solar radiation played a dominant role in determining the levels of both yield and transpiration, especially when water is non-limiting. Similar conclusions were drawn by Stanhill (1960) who plotted linear relations between cumulative dry matter production and cumulative evapotranspiration of grass grown at different latitudes. The highest slopes, and thus the highest water use efficiencies, were found in locations at higher latitudes (Denmark, Netherlands and England) and the lowest ones in Israel and Trinidad.

With the development of new and better equipment, such as climate-controlled glass houses and electronic equipment, more accurate measurements could be carried out. Bierhuizen and Slatyer (1965) conducted experiments on cotton leaves where airstreams with fixed temperature, humidity and CO_2 concentrations were passed through a leaf chamber. Photosynthesis and transpiration were measured as the difference in CO_2 and water vapour concentrations of air before and after passing through the leaf chamber. Using this experimental setup, the transpiration efficiency under different levels of air temperature, wind speed, CO_2 concentration and light intensities could be determined with higher accuracy. They were the first to claim and prove that transpiration and photosynthesis (and thus the

[1] "Silking" is when elongated stigmas, called silks, emerge from the whorl of husk leaves at the end of the ear of a maize plant.

transpiration efficiency) were more controlled by evaporative demand from the air, expressed as the vapour pressure deficit, than by radiation regimes or by latitude as claimed by De Wit (1958) or Stanhill (1960). This conclusion was later confirmed in a thorough review by Tanner and Sinclair (1983) who defined the water productivity relation as the transpiration efficiency which is the reciprocal of the transpiration ratio.

With the Green Revolution at its peak, numerous programmes were set up at universities and national research organizations to determine the optimal growing conditions for maximizing crop yields in farmer's fields. Whereas most experimental results from the first half of the 20th century originated from the western countries, the focus shifted to the developing countries in the later decades. International research organizations were established with large campuses to develop new crop varieties, make them available to the local farmers, and to provide optimal irrigation and fertilizer application strategies applicable to local conditions. Examples are the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, and the International Rice Research Institute (IRRI) in the Philippines and locally the Agricultural Research Council (ARC) in South Africa. With water resources being abundantly available in most new or expanding irrigation systems, research focused on maximizing crop yields for farmers by meeting the maximum crop water demands. Several models were developed that describe the relation between crop production and water use, with the purpose of determining the effect of crop water stress on yields. In South Africa, for example the Soil Water Balance (Annandale *et al*., 2005), MyCaneSim® (Singels, 2007), BEWAB (Bennie *et al*., 1998; Ehlers *et al*., 2007) and PUTU (De Jager, 1992 and 1994) models were developed.

The definition of Water Use Efficiency (WUE) is not unambiguous and needs some explanation since not all water professionals have the same interpretation and connotation. Water Use Efficiency was introduced in the 1950s for providing an extra indicator next to irrigation efficiency. The classical Irrigation Efficiency (IE) is meant to describe which portion of the water withdrawn from the source or applied at the farm gate, is available for root water uptake (e.g. Israelsen, 1932). Water Use Efficiency (WUE) intends to describe the crop production per unit of water consumed. These two concepts have both their own merits and are a great complementarity to describe key agricultural water management processes. Unfortunately, the concepts of IE and WUE are often confused and mixed-up. WUE is also expressed as water productivity in certain circles (e.g. Kijne *et al*., 2003; Zwart and Bastiaanssen, 2004), but in South Africa the term WUE is used, relating the harvestable yield to evapotranspiration. For clarity the definition used in this study for WUE holds as:

$$WUE = Y_{act} / ET_{act} \qquad (1)$$

where Y_{act} (kg/ha) is the crop yield actually harvested and ET_{act} (m^3/ha) is the actual evapotranspiration accumulated for the growing season. WUE can also be expressed as the above ground dry biomass produced per amount of evapotranspiration used in this process.

WUE has stimulated many agronomists and irrigation engineers to undertake field measurements and study whether the same crop yield can be acquired from less water. The result of all these studies is a large amount of literature that is written up in various research reports and journal articles. While this is a great asset for assessing the amount of food that can be produced from scarce water resources, the data is often biased toward the conditions typically encountered on experimental farms. It is believed that under practical on-farm management conditions, these values are not always plausible. Nevertheless, it is useful to compile data sets from individual research activities and establish databases on WUE.

There are at least 3 international data bases related to WUE. The longest existing knowledge center is the Food and Agricultural Organisation (FAO) which in their Irrigation and Drainage Report Series (nos. 33 and 66) report on the crop yield response to water (Doorenbos and Kassam, 1979; Steduto *et al*., 2012). Report 66 was recently published and a special expert consultation on closing gaps in land and water productivity has been organized (Sadras *et al*., 2013). FAO and WaterWatch have been working together in updating the international literature on WUE (Bastiaanssen *et al*., 2010). This database is available at FAO and has been used to verify the WUE computations from remote sensing techniques.

Satellite measurements can be utilized for the computation of biomass production and crop yield on the one hand and for actual evapotranspiration estimation on the other hand. These are the main inputs required for WUE estimation. Zwart *et al*. (2010) used this technology to infer WUE from satellite data for all mono-culture wheat areas in the world. This work was continued and improved by FAO for wheat, rice and corn. Similar work based on satellite data has been performed for grapes in the Western Cape (Klaasse *et al*., 2011; Jarmain *et al*., 2010).

The generic conclusion from all these remote sensing studies is that many areas contain a large variability of WUE, also between plots located in the same agro-ecological zone. There always exist some farmers with excellent irrigation and drainage practices. This shows that there is opportunity to improve WUE under local conditions and that the key for the solution has to be found locally.

Other databases on WUE are developed by the Water Footprint team (Mekonnen *et al*., 2012; Hoekstra, 2013). Their data base is prepared from statistical information of crop yield and a simplified calculation procedure for potential evapotranspiration and duration of crop cycles. The website www.waterfootprint.org provides tables with the average numbers of WUE by crop type. Liu *et al*. (2007) from the Chinese Academy of Sciences (CAS) used the GEPIC simulation model for computing the biomass production, crop yield and evapotranspiration (Williams, 1995). They have also developed a global database for WUE values for various crops and for different countries on the basis of a numerical simulation model.

It should be noted that the WUE statistics from the FAO, www.waterfootprint.org and the CAS databases are not identical. The difference can be ascribed to (i) the computational technologies used and (ii) spatial scale covered. For instance, satellites measure thousands of pixels and create a population of values from where certain statistics can be derived. The field measurements of the National Agricultural Research Stations represent a small area that is protected from diseases, droughts and other non-pristine conditions, which is basically a single point on the probability density function of satellite-based data sets of WUE.

The challenge is to engage with farmers to improve their WUE performance. The FruitLook project initiated by the Western Cape Department of Agriculture provides WUE information to individual farmers with information that is tailor made to their own plot. Local action can only be expected if farmers and their irrigation advisors can be guided individually. WUE is not measurable in the field, hence such measurement, monitoring and reporting system should be based on earth observations. Sending WUE related information to farmers is explored in certain African countries (e.g. Egypt, Sudan and Ethiopia; www.smartict-africa.com). Earth observation based irrigation advice is generally conceived as a useful alternative to soil moisture probes. Direct measurements of soil moisture show the moment of next irrigation but, these probes cannot be buried in every individual plot and can by default not measure WUE.

While increasing WUE is promoted by water agencies, farmers may have diverging short term views and perceptions (Wichelns, 2014). Farmers want to increase their returns ($) and are not inclined to invest in water saving technologies and take risks on crop damage and production gaps due to insufficient water supply. Yet, enforcements can bring them to other insights and farmers with a good feel for longer term solutions and sustainable farming realize that they should act now, in order to provide a solid basis for farming by their successors. It is not unlikely that future water licenses will be based on efficient water usage and that WUE will become an ultimate indicator for the provision of legal use water rights. The best solution is to expose farmers to the newest technologies to measure WUE and let the extension officers assist them with the interpretation, which this project aimed to do.

1.5 PROJECT OBJECTIVE AND AIMS

This project illustrates how spatially explicit information provided at frequent intervals can be used to determine, assess and potentially improve the water use efficiency of irrigated crops.

Specific project aims include:

- Confirming the degree of accuracy of evapotranspiration (ET), biomass, yield production and WUE estimated using the Surface Energy Balance Algorithm for Land (SEBAL) model (for selected crops and different spatial and temporal scales),
- Showing how spatially explicit ET and yield data generated using the SEBAL model can be used by different users (researchers, farmers, irrigation advisors and boards, water users associations) to assess and improve the WUE at different spatial scales (field, farm or larger) and for selected irrigated crops,
- Developing spatial WUE information generated with the SEBAL model to the point of operational use in South Africa and
- Building capacity (in students, researchers, extension officers, farmers, etc.) in the use of field and remote sensing based methods for improved WUE.

In this study examples of the use and value of remote sensing derived data for assessing and improving WUE within irrigated agriculture will be shown and the focus will be on high water using crops and crops extensively cultivated in SA (e.g. sugarcane, maize). This project will aim at conclusively confirming the degree of accuracy of the SEBAL model (when compared to traditional methods) for estimating ET and WUE of selected agricultural crops. It should pave the way for the operational near-real time application of RS data in agricultural water management in future. Collaboration with potential users of the data (researchers, farmers, irrigation advisors, IB/WMA) and continued capacity building (students, extension officers, researchers) in generating and using this data is key to the success of this project.

1.6 STUDY APPROACH AND NOTES

In order to address the set objective and aims, two economically important agricultural crops were selected namely sugarcane (*Chapter 2, 4*) and maize (*Chapter 3, 5*). Data derived from the spatially explicit SEBAL model was compared to field observations and data derived from models traditionally used in South Africa to model water use efficiency (*Chapters 2, 4*). The accuracy of these data sets are described (*Chapters 3, 5*) and the usefulness and application of the data sets discussed (*Chapter 8*). Capacity building and knowledge transfer were important aspects of the project (*Chapter 6, 7*), focusing not only on students, but also on researchers, farmers and industry partners. The general project approach is summarised in Figure 1.

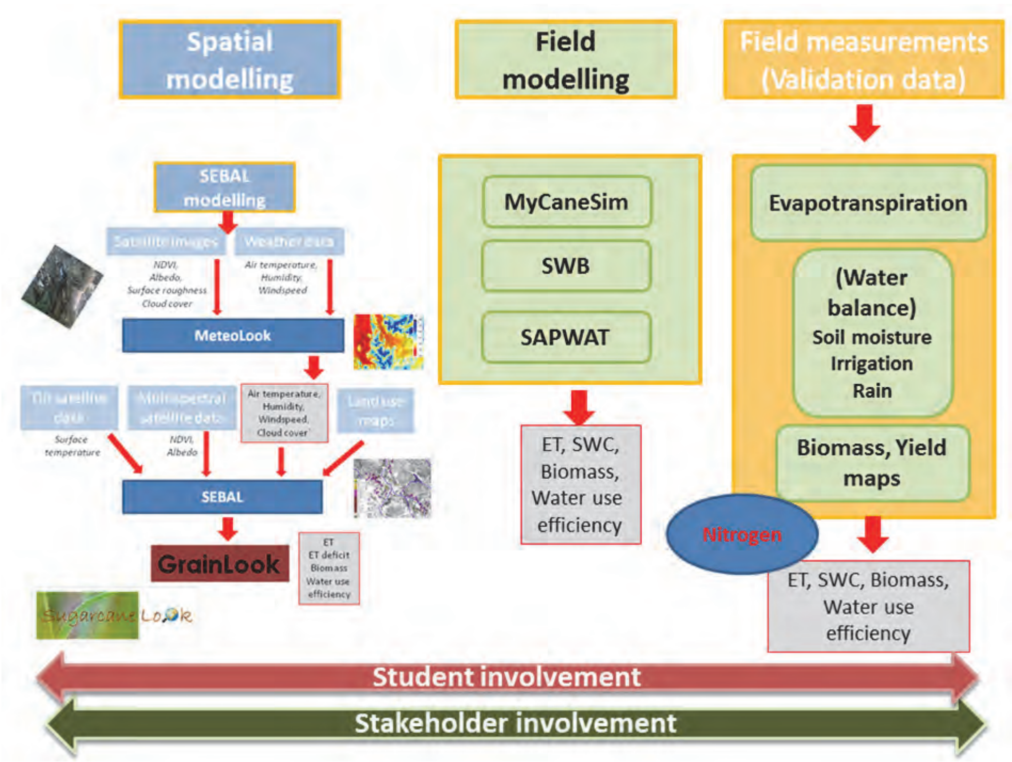


Figure 1. Schematic of the general research approach followed in this project

NOTE: In this project, the accuracy of the SEBAL results is assessed mainly against estimates from established models and limited amounts of field measured data. Estimates could hence refer to either modelling results or where field measurements were used in the calculations (indirect measurement). Modelled results are also referred to as simulated data represents estimates; forecasted data which is also simulated with models are explicitly specified as being forecasts.

CHAPTER 2: ESTIMATING WATER USE EFFICIENCY OF IRRIGATED SUGARCANE

2.1 STUDY AREA 1: IRRIGATED SUGARCANE

Sugarcane is mainly grown on the eastern side of South Africa, from the Mpumalanga province in the north, throughout KwaZulu-Natal, up to the Eastern Cape in the south (Figure 2). Sugarcane is exclusively produced under irrigation in Mpumalanga, whereas it is produced under irrigated and rainfed conditions in KwaZulu-Natal and the Eastern Cape.

Figure 2. Extent of sugarcane production in South Africa, illustrating both irrigated and rainfed areas as well as the sugarmills
[Map source: SASA, http://www.sasa.org.za/Libraries/Maps/Map_of_Operational_Areas.sflb.ashx]

The sugarcane producing areas around Malelane and Komatipoort represented the greater study area (Figure 3). Komatipoort is situated approximately 54 km's East of Malelane at 170 m.a.s.l. compared to the 301 m.a.s.l. of Malelane. Both these areas are characterised by very hot summers and mild winters. The long term mean (LTM) annual rainfall of the Komatipoort area is 654 mm which is 16 % (122 mm) less than what the Malelane area receives. Approximately 3% more solar radiation is received in the Komatipoort area. The LTM monthly average maximum and minimum air temperatures in the Komatipoort area is respectively 0.9 ˚C and 0.5 ˚C higher than that of the Malelane area. However in winter months the LTM minimum air temperatures at Komatipoort are up to 1.9 ˚C lower than for Malelane. Interestingly enough the LTM monthly mean relative humidity in the Komatipoort area is 5% lower than that of the Malelane area. The opposite is true for the winter months. The net result due to all these differences is that the evaporative demand (and thus crop water use), is significantly higher in the Komatipoort area. For example the LTM reference cane evapotranspiration for the Komatipoort area is 1736 mm/ annum compared to 1475 mm/ annum for the Malelane area. For the Crocodile River (Malelane area) the allocated water quotas is 13 000 m^3/ha/annum and for the Komati River (Komatipoort area) the quota is 9950 m^3/ha/annum. These quotas are sufficient to satisfy crop water demand in the Malelane area (approximately 1228 mm), but only partially for the Komatipoort area (approximately 1386 mm).

2.1.1 Selected fields

Within the greater study area, thirteen sugarcane fields were selected for monitoring crop growth and soil water status (Figure 4). Each field is described in terms of cultivar, row spacing, plant and harvest dates (2012, 2013 seasons), irrigation system deployed and irrigation cycle (Table 1).

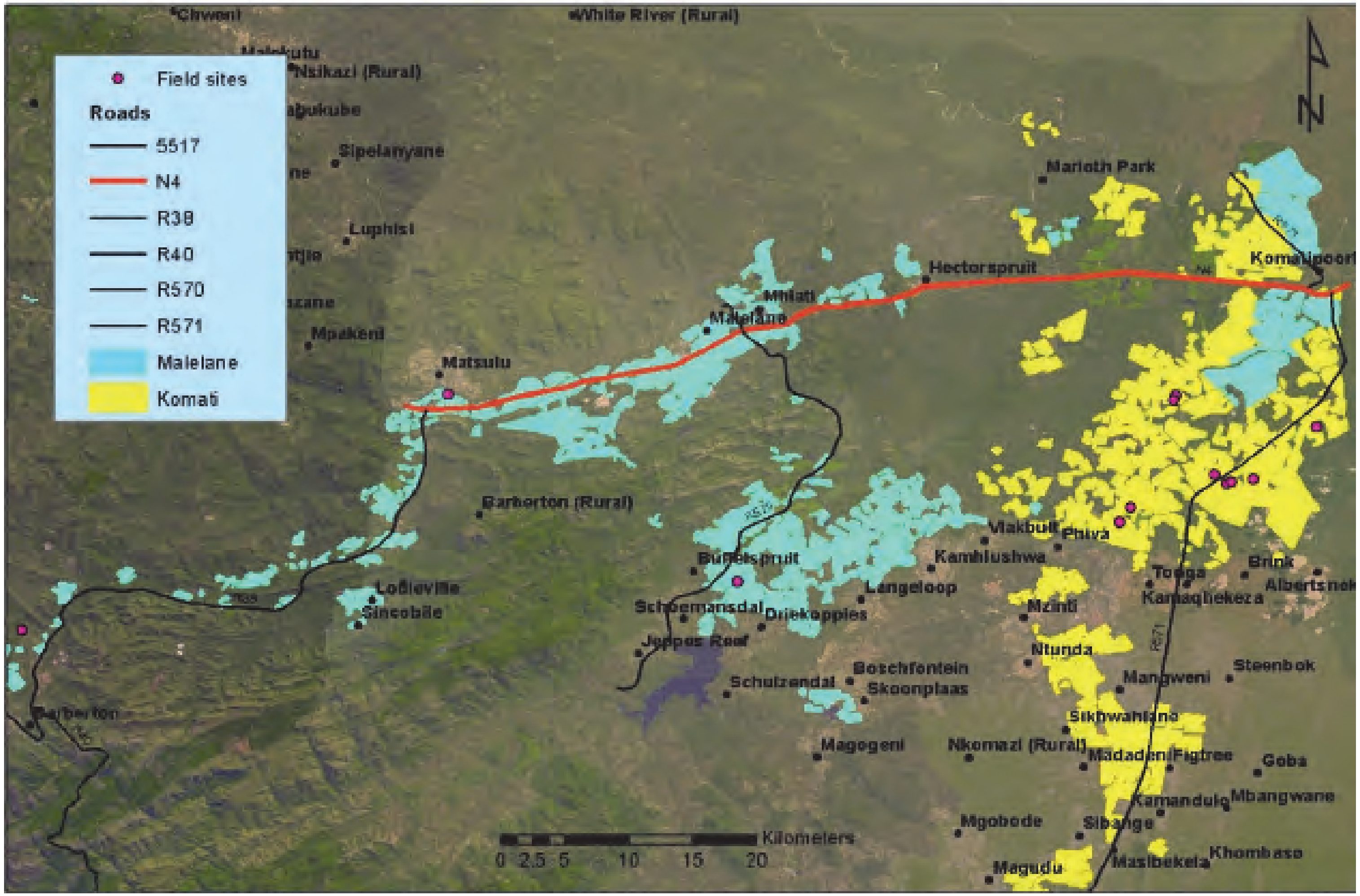


Figure 3. An outline of the overall sugarcane study area, showing the extent of the sugarcane fields delivering to the Malelane (blue areas) and Komatipoort mills (yellow areas) (taken from Cloete, 2012)

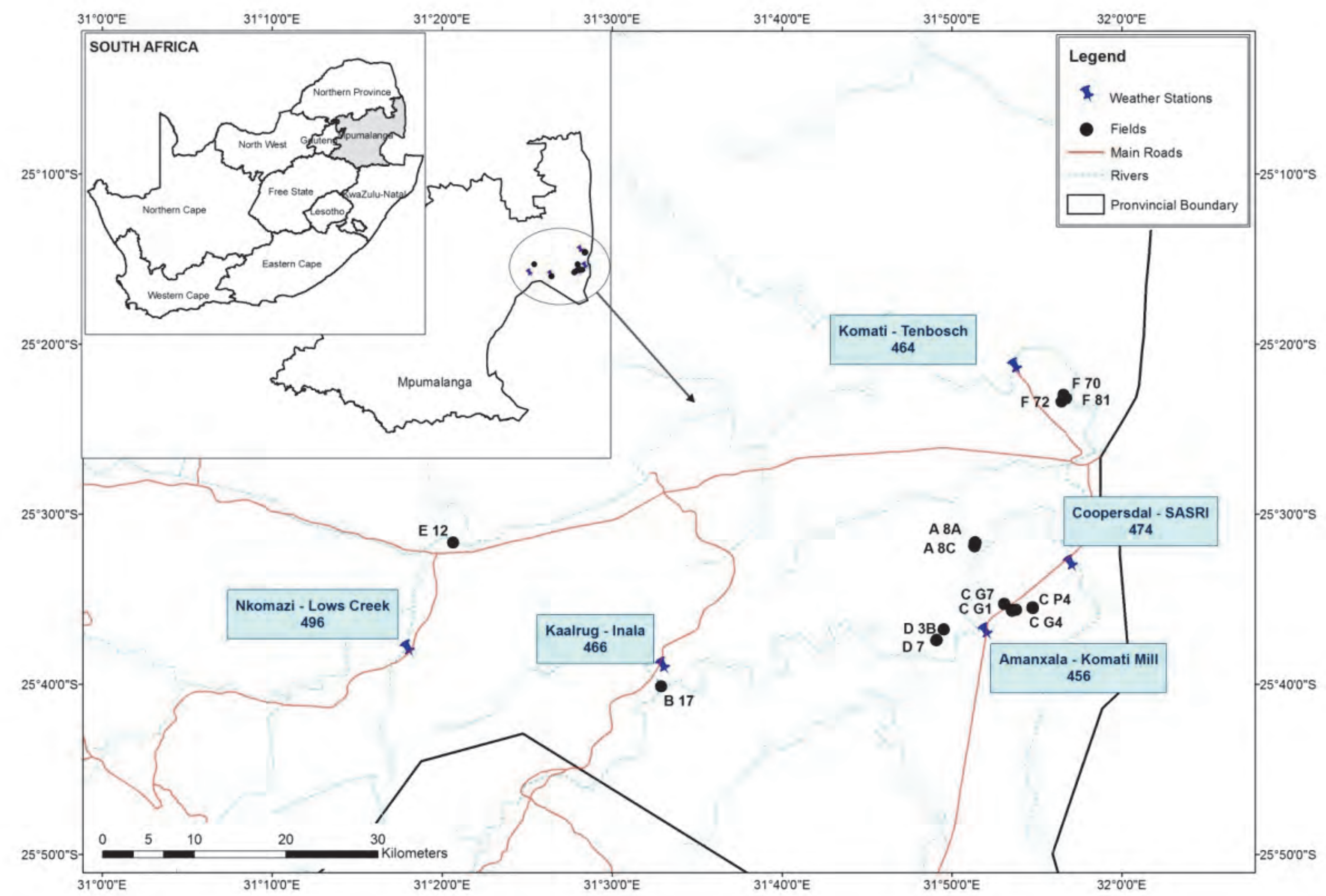


Figure 4. Map of the study area showing the location of thirteen monitoring sites and weather stations. The study area is situated in the eastern part of the Mpumalanga province, which is situated in the north east of South Africa (produced by the GIS office, South African Sugarcane Research Institute).

Table 1. Field details for different sites and simulation settings for the CaneSim® sugarcane model.

Farm code	Field Name	Rooting depth (m)	Clay content (%)	TAM [2] (mm)	Automatic weather station [3]	Variety	Row spacing (m)	Crop start date 2011	Crop harvest date 2012	Crop harvest date 2013	Irrig. system [4]	Irrig. cycle (d)	Irrig. amnt [5] (mm)	ADL [6] (mm)
A	8A	0.77	36	102	Coopersdal – SASRI	N25	1.1 [7]	31/Jul/2011	29/Jun/2012	07/Jul/2013	SD [8]	1	7	71
A	8C	0.75	45	96	Coopersdal – SASRI	N25	1.1 [4]	31/Jul/2011	28/Jun/2012	11/Jul/2013	SD	1	7	70
B	17	0.68	71	61	Kaalrug – Inala	N25	0.95 [4]	08/Sep/2011	25/Aug/2012	01/Nov/2013	OH [9], SD	7 2	24 9	42 42
C	G1	0.72	39	93	Amanxala - Komati Mill	N19	1.5 [10]	11/Jun/2011	14/Jun/2012	27/Jun/2013	SD	1	7	65
C	G4	0.72	38	94	Amanxala - Komati Mill	N19	1.5 [5]	24/Jun/2011	16/Jun/2012	23/Jun/2013	SD	1	7	65
C	G7	0.60	39	78	Amanxala - Komati Mill	N14	1.5 [5]	08/Aug/2011	04/Jul/2012	No crop	OH	2	12	56
C	P4	0.70	41	90	Amanxala - Komati Mill	N32	0.9 [4]	14/Oct/2011	14/Dec/2012	26/Nov/2013	SSD [11]	1	7	63
D	3B	0.40	27	54	Amanxala - Komati Mill	N19	1.1 [4]	12/May/2011	20/Jun/2012	02/Nov/2013	SD	1	6	36
D	7	0.72	36	80	Amanxala - Komati Mill	N19	1.4 [5]	01/Jul/2011	08/Jun/2012	Ploughed out	OH	7	48	56
E	12	0.75	20	96	Nkomazi - Lows Creek	N32	0.95 [4]	21/Jul/2011	21/Jul/2012	03/Aug/2013	SD	3	8	67
F	70	0.57	25	76	Komatipoort – Tenbosch	N36	0.95 [4]	19/May/2011	21/May/2012	29/Jun/2013	SD	1	6	53
F	72	0.70	43	89	Komatipoort – Tenbosch	N23	1.5 [5]	12/Sep/2011	23/Oct/2012	13/Sep/2013	OH	2	15	62
F	81	0.73	46	90	Komatipoort – Tenbosch	N36	0.95 [4]	22/May/2011	26/May/2012	26/Jun/2013	SD	1	6	63

[2] TAM is the maximum amount of water in the root zone available to the plant when the profile is at field capacity. TAM is estimated from soil texture and rooting depth following van Antwerpen *et al*. (1996)

[3] Campbell Scientific Inc., North Logan, Utah

[4] Irrig. refers to irrigation.

[5] Irrigation amount (Irrig. amnt) is the design irrigation amount per event

[6] ADL is the chosen allowable depletion level at which point an irrigation is triggered.

[7] Tram line configuration

[8] SD = surface drip

[9] OH = overhead (centre pivot or dragline)

[10] Single line configuration

[11] SSD = sub-surface drip

2.1.2 Study period

The original study period extended from 1 November 2011 to 31 October 2012. Since this period does not cover a typical sugarcane growing season, but rather span two growing seasons partially, the study period was extended to 31 July 2013. Sugarcane is planted throughout the year, with the exception of the months of June and July, when the temperatures are too low.

To enable us to extend the study period, the following actions were taken:

- SASRI, as part of their continued research activities, continued to monitor and collect field data and model the water balances for 11 selected fields for an extended period (until 30 November 2013).
- Through the WatPLAN project executed in the Incomati catchment (and funding from both the ICMA and the EU), eLEAF provided the spatial data for this extension period for the 13 selected fields.
- SASRI, at own cost, acquired an additional month's spatial data, to complete the sugarcane 12 month growing season and hence extending the study period to 31 July 2013.

2.2 FIELD MEASUREMENTS

For thirteen selected irrigated sugarcane fields (Table 1, Figure 4), field measurements related to crop development and the soil water balance (soil water content, rainfall, irrigation and evapotranspiration) were obtained. Apart from the evapotranspiration field observations which were taken from December 2011 to December 2012, all other field measurements were made throughout the study period. A summary of the measurements, their frequency and repetitions, are given in Table 2.

Table 2. A summary of field measurements related to sugarcane crop development and the water balance taken, showing measurement frequency and repetitions

Crop development (measurement, frequency, repetition)			Soil water balance (measurement, frequency, repetition)		
Stalk population	Monthly	5 m section X 3 x 13 locations	Soil water index	Continuous	30 min. X 13 locations
Stalk height	Monthly	10 stalks X 3 x 13 locations	Irrigation	Continuous	30 min. X 13 locations
Canopy cover (fractional interception)	Monthly	10 readings X 3 x 13 locations	Rainfall	Continuous	30 min. X 13 locations
Mass of leaves, stalks and stalk sucrose	Every 4 months	5 stalks X 3 x 13 locations	Energy balance[12]	Continuous	30 min. X 1 location
Cane and sucrose yield	At harvest	Whole field x 13 locations	Evapo-transpiration[12]	Continuous	30 min. X 1 location

2.2.1 Soil water content

Fields on farm F had continuous logging capacitance probes from Aquacheck (Pty) Ltd., (Durbanville, South Africa) installed on them prior to the 2011/12 cropping season. Aquacheck capacitance probes were installed on all the other fields listed in Table 1, some in November 2011 and some in March 2012. Probes had six sensors spaced at depth intervals of 100 mm (60 cm probes) or four sensors spaced at 100 mm intervals with two more at 600 and 800 mm (80 cm probes). Equal weightings were used for all sensors of a given probe, regardless of the sensor spacing. This reflected the assumed lower rooting density in the bottom two layers of a 80 cm root zone where sensors were spaced at 200 mm rather than 100mm. Probes were installed as close as possible to the cane row or immediately next to drip emitters

[12] Evapotranspiration field observations which were taken only from December 2011 to December 2012

(in the case of drip irrigated fields) by inserting them in a vertical cavity created by a soil auger and filling any remaining space between the probe and the cavity wall with slurry. Tipping bucket rain gauges were also connected to probe transmitters to measure rainfall and or irrigation. Details on the installations are not included here.

Gravimetric soil samples were collected on a few occasions to estimate volumetric soil water content at depths of 20, 40 and 60 cm. It was hoped that this could be used to determine the reliability of probe data. Instead it was very difficult to get reliable gravimetric estimates due to spatial variation in soil water content especially in drip irrigated fields and hence results regarding the reliability of the probe data are inconclusive.

2.2.2 Evapotranspiration measurements

Evaluating the accuracy of estimates of evapotranspiration was an important part of this project. A surface renewal (SR) system (Savage *et al*., 2010 and Olivier *et al*., 2010) was installed to estimate the energy balance and ET from field G1 (Farm C) (Figure 5). Measurements took place from December 2011 to December 2012. The SR method estimates the sensible heat flux density and combining this with estimates of net radiation and soil heat flux, the latent energy and ET is estimated using the energy balance equation. The surface renewal method is attractive due to its simplicity (few parameters needs to be measured) and it is relatively low cost, but the method requires knowledge of the crop and measurement height, the rate of change in air temperature and a weighting factor. The weighting factors need to be determined, *a priori*, for the vegetation type, thermocouple size and measurement height by comparing the SR estimated sensible heat flux density with sensible heat flux density measurements from another method e.g. the eddy covariance methods. Weighting factors are available for a number of crops e.g. for sugarcane (Nile, 2010 and Olivier *et al*., 2010).

Surface renewal system calibration against an Open Path Eddy Covariance (OPEC) system from 24 July to 17 September 2012 (Figure 5) was used to derive parameters needed to apply the SR during this period. For the remaining period, published parameters were reviewed (see Jarmain *et al*., 2013), but in the end parameters applied relied on expert opinion (Oliver, 2014 and Mengistu, 2012).

For the period of system calibration, the sensible heat flux densities (H) from the SR system (alpha=1; lag=0.4) were compared to the estimates from the eddy covariance systems (Figure 6). The comparison showed that the surface renewal system H values, using an alpha of 1, exceeded the sensible heat fluxes from the eddy covariance (R^2=0.7316 and slope=0.6336). This data set was used to develop a weighting (alpha) factor for use for this calibration period. A lag time of 0.4 was used throughout. An alpha value of 0.6 was used for the calibration period. The alpha values used for the remaining period are shown in Figure 7. The alpha values used are also plotted against the Days after planting (DAP), together with that derived by Olivier (2014).

Figure 5. Surface renewal system (*left*) installed in the sugarcane field UVS G1 with the Eddy covariance system (*right*) installed for calibration purposes

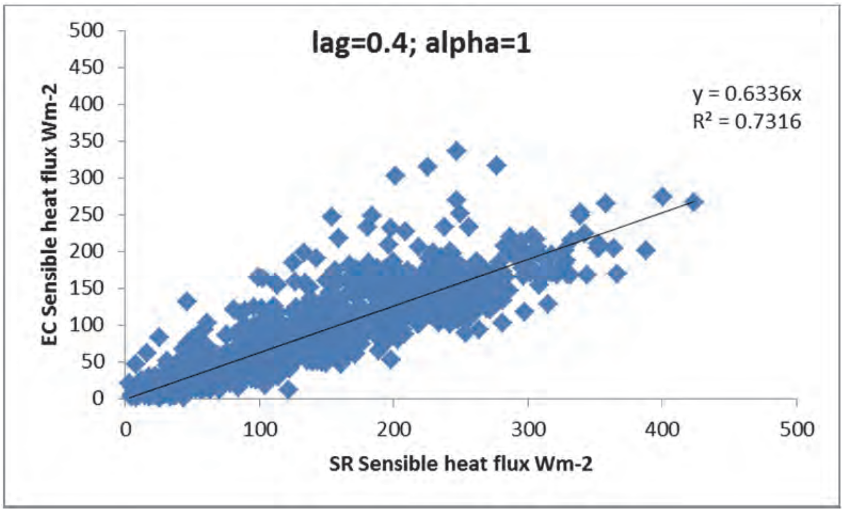


Figure 6. For SR system calibration, the sensible heat flux densities was compared to that from an eddy covariance system

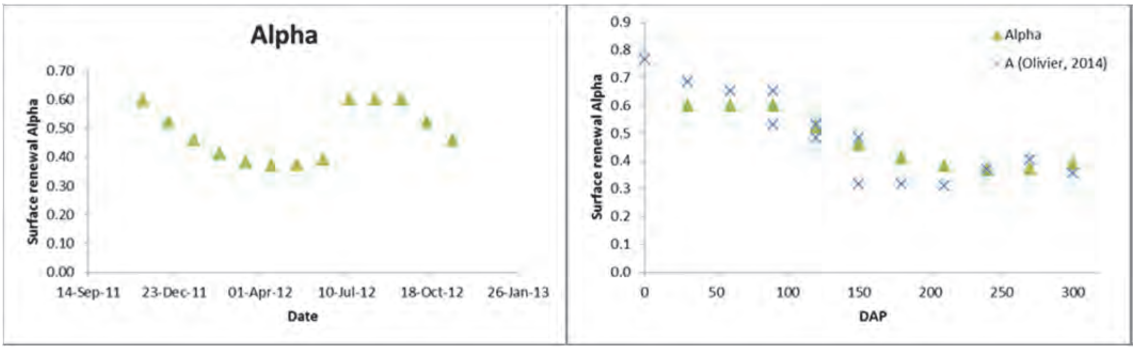


Figure 7. Alpha values used to estimate sensible heat flux using the surface renewal method. Left: Actual alpha values used, against dates and right: Alphas (used and by Olivier, 2014) plotted against days after planting (DAP).

2.2.3 Crop growth data

Canopy cover (CC) was estimated by measuring interception of Photosynthetically Active Radiation (PAR) with a portable line quantum sensor (Model AccuPar LP80, Decagon Devices, Pullman, USA) at approximately monthly intervals in three positions in each field. Ten readings per position were taken.

Biomass components were sampled destructively two to three times through the growing season in each field. Three 5 m row sections were randomly selected to determine the stalk population. Within each section five representative cane stalks were cut and removed. Biomass samples were partitioned into leaf material and millable stalk material. Fresh samples of each component were weighed. Sub-samples of these were weighed, dried and weighed again to determine the dry matter content of each component. Dry leaf mass and dry stalk mass were calculated as the product of fresh mass and dry matter content of the relevant component. Dry aboveground biomass was taken as the sum of dry leaf mass and dry stalk mass. At harvest, cane yield (fresh mass basis) was determined from mill delivery data. Delivered cane were analysed for dry matter content and sucrose content, which allowed the derivation of stalk dry mass yield and sucrose yield at harvest. Cane yield is fresh mass and the typical moisture content at harvest range between 80 and 65%. The actual cane yield is determined as part of the standard analysis at the mill, so that stalk dry mass fiber mass , brix mass and sucrose mass can be derived.

It was found that the average cane yield for a field as determined from mill deliveries, where mostly significantly lower than the cane yield determined form destructive samples taken from selected spots in the field before the actual harvest. This was an indication that there were areas in the field that had lower above ground biomass yields and that the field sampled estimates of average yields of the different biomass components (stalk and leaf mass) were overestimated. It was therefore deemed necessary to adjust observed biomass data. This was done by multiplying all observed biomass data values by the ratio of mill determined cane yield to the field cane yield sample taken just before harvest, if the time difference was less than one month. The average ratio for the two seasons was used to adjust biomass data for both seasons. In one case (field 7) no suitable field sample data were available to estimate an adjustment factor and overall average adjustment factor for all fields were used. Details are given in Table 3.

Table 3. Data used to derive factors for adjusting observed biomass sample data to represent field average values better

Season	Field name	Field sampled stalk dry mass (last sample before harvest) (t/ha)	Mill delivered stalk dry mass (t/ha)	Difference between harvest date and sample date (d)	Ratio between field sampled stalk dry mass and mill delivered stalk dry mass	Adjustment factor	Average adjustment factor over two seasons
2012	8A	19.90	25.66	119	1.29		
2012	8C	38.47	24.90	7	0.65	0.65	
2012	17	9.49	22.00	168	2.32		
2012	3B	27.95	25.24	7	0.90	0.90	
2012	7	18.53	23.18	98	1.25		
2012	12	29.24	31.16	14	1.07	1.07	
2012	70	53.61	34.43	7	0.64	0.64	
2012	72	45.43	44.85	42	0.99		
2012	81	39.69	33.74	14	0.85	0.85	
2012	G1	47.62	31.98	14	0.67	0.67	
2012	G4	48.22	37.14	14	0.77	0.77	
2012	G7	33.83	30.49	-6	0.90	0.90	
2012	P4	51.01	35.63	84	0.70	0.70	
2013	8A	46.59	28.50	7	0.61	0.61	**0.61**
2013	8C	44.00	27.93	7	0.63	0.63	**0.64**
2013	17	46.01	34.46	7	0.75	0.75	**0.75**
2013	3B	44.81	31.87	28	0.71	0.71	**0.81**
2013	7						
2013	12	49.79	30.52	14	0.61	0.61	**0.84**
2013	70	41.16	35.91	14	0.87	0.87	**0.76**
2013	72	45.29	36.85	0	0.81	0.81	**0.81**
2013	81	46.70	36.01	7	0.77	0.77	**0.81**
2013	G1	46.97	34.12	14	0.73	0.73	**0.70**
2013	G4	41.10	40.99	7	1.00	1.00	**0.88**
2013	G7						**0.90**
2013	P4	33.20	33.20	27	1.00	1.00	**0.85**
Average						**0.78**	

2.3 INTEGRATION OF SOIL WATER MONITORING WITH MYCANESIM ®

2.3.1 System description

Near real-time field recordings of soil water content, rainfall and irrigation were incorporated into the MyCaneSim® system to evaluate its use for supporting irrigation management in the 13 sugarcane fields described in Table 1. The value of correcting simulated soil water content and inferring irrigation input data from the field records for reviewing irrigation practices and for guiding irrigation scheduling, were assessed with participating farmers. The system was also used to assess irrigation and agronomic management on these fields using simulated and observed data.

The MyCaneSim® system is described by Singels (2007) and Singels and Smith (2006). Briefly, it consists of the CaneSim® sugarcane simulation model linked to an on-line weather and field database, and an irrigation scheduling and advice module. The system uses basic field data (e.g. soil water holding capacity, cropping details and irrigation system properties) initially entered by the user *via* a web-based interface, to estimate the soil and crop status for each day of the growing season (Figure 8). The system can be used to analyse agronomic performance of past seasons or to predict water use, irrigation requirements and yields for the current season.

The following aspects of the system are described in more detail below:

- Conversion of soil water status data, as recorded by capacitance probes, to root zone available soil water content (ASWC) and the integration thereof into the MyCaneSim® database,
- Resetting simulated ASWC with field recorded ASWC,
- Inferring irrigation events from field recorded soil water status data, and
- Reporting of simulated water balance and crop status output.

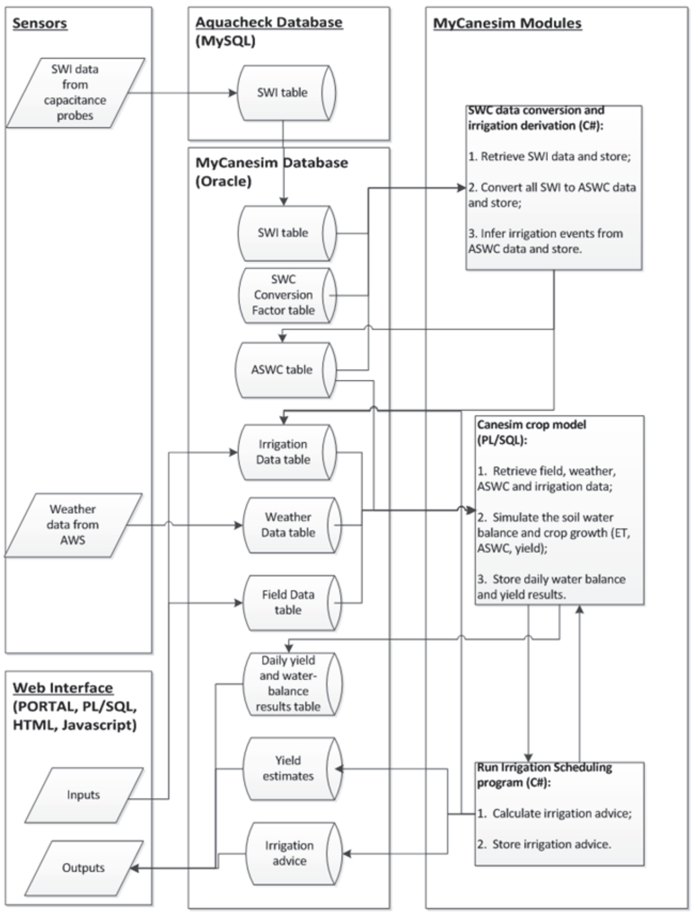


Figure 8. A flowchart summarizing components and data flow of the integrated MyCaneSim® sugarcane simulation system. Software components include: MySQL database, Oracle PORTAL 11, Oracle PL/SQL 10.0.5 and Oracle database 10g (Oracle Corporation, Redwood Shores, California, www.mysql.com and www.oracle.com) and Microsoft Visual C# 2010 (Microsoft, Redwood, Washington,www.microsoft.com). SWI refers to soil water index and ASWC refers to available soil water content.

2.3.2 Soil water status data conversion and integration

Capacitance probes estimate soil water status by measuring the electrical permittivity of soil (Evett *et al.*, 2006; Gardner *et al.*, 1998; Paige and Keefer, 2008; Zerizghy *et al.*, 2013). Probes typically have several sensors spaced at intervals of 100 mm and can cover the root zone up to a depth of 1.8 m. The sensors typically output soil water index readings (SWI in %), derived from a factory calibration relating sensor signal to a value of 0% for air and a value of 100% in water. Probes can be connected to transmitters that automatically transfer data to a central server *via* the cellular phone network or through radio signal.

The assumption is that the relationship between SWI and ASWC is linear and that the coefficients of linearity would differ from field to field as determined by sensor and soil properties.

Recorded soil water status of the root zone (the average SWI of all available sensors in the profile) was transformed to units of ASWC using two field specific calibration factors, namely (1) the SWI at field capacity (FC_{SWI} in %), and (2) a conversion ratio (CR in mm/%, defined as the amount of available soil water per unit of SWI):

$$ASWC = TAM - CR(FC_{SWI} - SWI) \quad (2)$$

where TAM[13] is the plant available soil water content of the root zone at field capacity after drainage of free water (in mm). Eq. 2 reflects the assumed direct proportionality between soil water deficit (the difference in water content at field capacity and current water content) measured by sensors (FC_{SWI} – SWI) and quantified in units of available water (TAM – ASWC). Values for FC_{SWI} were determined by investigating recorded drainage and extraction patterns after a wetting event. Significant wetting of an already wet root zone will increase SWI above the FC_{SWI}, causing rapid drainage and decline of SWI over time. As soon as the SWI reaches FC_{SWI}, drainage rate and decline in SWI would slow markedly, indicating the transition from rapid drainage of free water to extraction of water by plants, providing an indication of the value of FC_{SWI}. Values for CR were determined by comparing recorded extraction rates for dry days with MyCaneSim® simulated extraction rates and adjusting CR values until these extraction patterns (average rates of decline in simulated and observed ASWC) matched. CR values can also be determined by comparing recorded responses to night-time wetting events of known amounts of water but this was not used here because reliable irrigation and local rainfall records were not available.

Half-hourly SWI data were transferred from a central Aquacheck server to the MyCaneSim® database, and then converted to ASWC. The ASWC value at 8:00 am is taken as the daily value that is displayed on soil water graphs. The user can also manually upload ASWC data into the database through the MyCaneSim® web interface. Users need to specify whether they want simulated ASWC to be corrected with measured values or not. If the correction option is chosen, the simulated ASWC at the start of the day will be reset to the measured value, except on days when rainfall or irrigation exceeded 15 mm. This exception was required to avoid potential errors that could be caused by the uncertainty of whether the wetting event occurred before or after the time of the measured ASWC.

2.3.3 Inferring irrigation input for MyCaneSim® from soil water status data

Accurate irrigation data is necessary for accurate simulation of the soil water balance (when measured soil water status is not used to correct simulations) and subsequent simulations of crop growth and yield. It is also required for evaluating and understanding the management of irrigation water and its efficiency of use. Although the MyCaneSim® system has a facility for users to upload irrigation data (dates and amounts), it is seldom used, possibly because users don't have accurate records or they find it too time-consuming. In this study, no reliable irrigation records were available. For these reasons, irrigation data were inferred from changes in field recorded soil water status and weather station recorded rainfall.

[13] TAM is an established acronym used in the S.A. sugar industry and is also used in the MyCanesim® system.

2.4 CROP WATER REQUIREMENTS MODELLED WITH SAPWAT

The SAPWAT model is an irrigation planning and management tool rather than a crop growth model or irrigation scheduling tool (Crosby and Crosby, 1999). SAPWAT is based on the CROPWAT model developed by the FAO (Smith, 1992) and is typically used to estimate crop water requirements. The latest version, SAPWAT3, has been extensively applied in South Africa for the estimation of crop irrigation requirements by irrigation engineers, planners and agriculturalists (van Heerden *et al*., 2008) and was used in this study.

SAPWAT3 was set up for the selected fields using relevant soil depth, irrigation system, planting and harvesting dates and associated weather station data (Table 4). In all the simulations, longterm daily average weather data was used to estimate evapotranspiration for an optimally irrigated sugarcane crop.

Table 4. SAPWAT3 parameters used in modelling of thirteen sugarcane fields

Farm, Field code	Rooting depth (m)	Weather station	Irrigation system	Start date	Harvest date
A, 8A	0.77	Coopersdal	Surface drip	2011/07/31	2012/06/29
A, 8C	0.75	Coopersdal	Surface drip	2011/07/31	2012/06/28
B, 17	0.68	Kaalrug	Dragline	2011/09/08	2012/10/31
C, G7	0.48	Amanxala	Centre pivot	2011/08/08	2012/07/04
C, G1	0.72	Amanxala	Surface Drip	2011/06/11	2012/06/11
C, G4	0.72	Amanxala	Surface drip	2011/06/24	2012/06/11
C, G7	0.7	Amanxala	Sub-surface drip	2011/10/14	2012/10/02
D, 7	0.72	Amanxala	Centre pivot	2011/05/12	2012/06/20
D, 3B	0.4	Amanxala	Surface drip	2011/07/01	2012/06/08
E, 12	0.75	Lows Creek	Surface drip	2011/07/21	2012/07/26
F, 70	0.57	Croc-Bridge	Surface drip	2011/05/19	2012/05/21
F, 72	0.7	Croc-Bridge	Centre pivot	2011/09/12	2012/10/23
F, 81	0.73	Croc-Bridge	Surface drip	2011/05/22	2012/05/26

SAPWAT3 utilises a four-stage crop development curve procedure, where the crop evapotranspiration (ET) of a specific growth stage is related to short grass reference evapotranspiration (or ET_o) by applying a crop coefficient. In SAPWAT, typical values of expected average sugarcane crop coefficients under a mild, standard climatic condition from the FAO 56 publication were used. SAPWAT3 provides default stage length values for each of the five climatic zones and has options to modify crop coefficients for different cultivars and planting dates. In order to include corrections for climate, users can manipulate the planting date, management strategies and length of the crop growing stages (Van Heerden *et al*., 2008). The length of crop developmental stages used to estimate ET is provided in Table 5. The crop coefficients used were 0.10, 1.2 and 0.7 for initial, mid and late crop stages, respectively.

Table 5. Length of crop developmental stages of sugarcane at a rage of planting dates used in the SAPWAT modelling

	Crop growing stages (days)			
Planting month	Initial	Developmental	Mid	late
May	40	170	100	66
July	40	150	130	56
Sep	30	110	180	46

2.5 SPATIAL MODELLING

Water use efficiency was modeled spatially using the Surface Energy Balance Algorithm for Land (SEBAL) model.

2.5.1 Surface energy balance algorithm for land model description

The Surface Energy Balance Algorithm for Land (SEBAL) model was formulated by Bastiaanssen *et al*. (1998a, b). Numerous researchers and the consulting firm eLEAF (previously WaterWatch) contributed to the extensive evaluation and further development of this model, especially for operationally purposes. SEBAL is widely described: see for example Meijninger and Jarmain (2014).

SEBAL estimates the components of the energy balance (Eq. 3) defined as

$$LE = R_n - G - H \qquad (3)$$

where LE is the latent energy flux density, Rn the net radiation, G soil heat flux density and H sensible heat flux density. The Latent energy flux density is equivalent to evapotranspiration (ET). In order to estimate ET, SEBAL solves a set of equations in a strict hierarchical sequence to convert spectral radiances measured by satellites into estimates of the surface energy balance. Inputs on land characteristics and atmospheric properties such as the vegetation index, surface albedo, surface temperature and cloud cover are derived from satellite data. SEBAL requires spatially extrapolated meteorological data (wind speed, humidity and air temperature) from local weather stations and a digital elevation map (DEM). SEBAL provides spatial estimates of various parameters, of importance to this project evapotranspiration, crop potential evapotranspiration and biomass production at pixel scale (Figure 9).

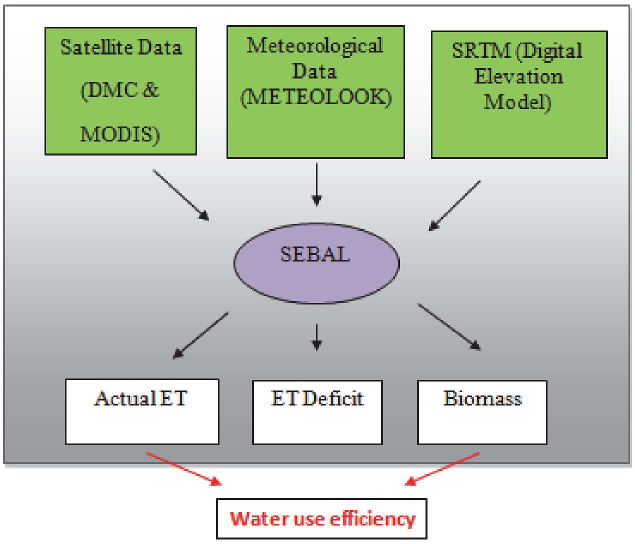


Figure 9. Diagram showing important data inputs and outputs (ET, ET_{def}, Biomass) from the SEBAL model

2.5.1.1 Evapotranspiration

SEBAL estimates actual evapotranspiration (ET) from a combination of remote sensing and field data in a number of processing steps (Figure 10). First SEBAL solves the instantaneous shortened energy balance for the time of satellite overpass. The net radiation and soil heat flux density is first estimated and then the sensible heat flux density is derived from special 'anchor' pixels within the thermal satellite image. The selected 'anchor' pixels consist of a 'wet' pixel (often water) and a 'dry' pixel, representing areas where the ET is considered maximum and close to zero respectively. The latent energy flux density is estimated as the residual of Eq. 3, taking into account the evaporative fraction (EF):

$$EF = LE/(R_n - G) \quad (4)$$

In a second step, the daily energy balance is solved, assuming that the evaporative fraction remains reasonably stable during a day (Figure 10). An advection model allows for the daily evaporative fraction to change due to advection processes. Advection refers to the horizontal exchange of energy due to horizontal heterogeneity at the earth's surface which can alter ET. Once the daily net radiation and soil heat flux density is estimated, the daily ET can be derived.

The Penman-Monteith equation (Allen *et al*., 1998) is subsequently used in reverse order to estimate the daily average surface and crop resistance. This resistance is used in the final step to estimate the ET using the Penman-Monteith equation for a period, in this project a week. SEBAL assumes that the daily stomatal resistance remains fairly constant during a week hence it is not adjusted after a rainfall event. Evapotranspiration is expressed in mm/week.

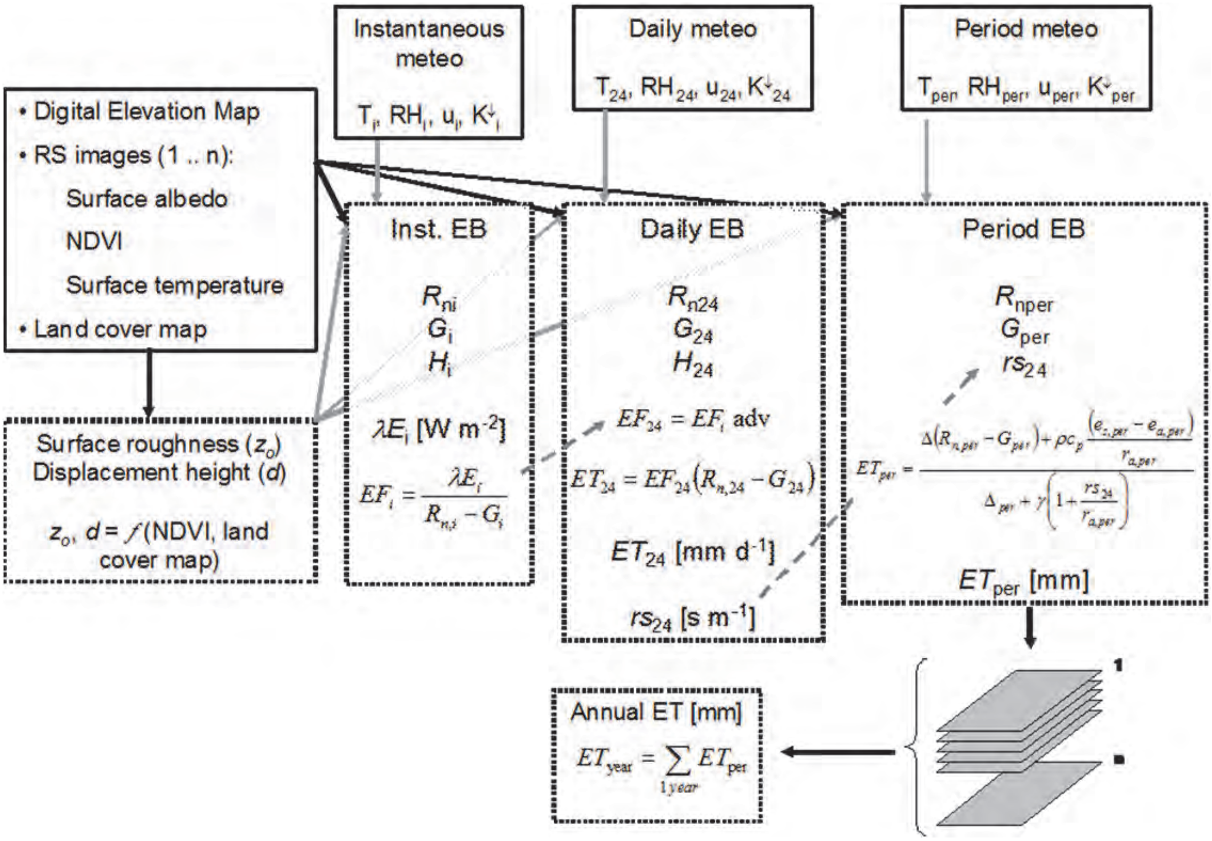


Figure 10. Processing steps performed in the SEBAL model to first derive the surface energy balance and evapotranspiration (ET) at the time of satellite overpass, then for a DAY and lastly for a weekly period

2.5.1.2 Potential evapotranspiration

SEBAL estimates the potential evapotranspiration (PET) from a surface, which can be defined as the amount of water that could be evaporated and transpired if sufficient water was available. The potential ET is estimated using the Penman-Monteith equation where the surface resistance (r_s) is not limited by the water that could be evaporated and transpired.

2.5.1.3 Evapotranspiration deficit

SEBAL estimates an evapotranspiration deficit (ET_{def}) as the difference between the potential and actual evapotranspiration. Any evapotranspiration deficit is an indicator of plant (water or other) stress since it reflects an evapotranspiration shortfall from the potential evapotranspiration rate. Evapotranspiration deficit is expressed in mm/week.

2.5.1.4 Biomass production

The biomass production in SEBAL refers to total above plus below ground dry matter production. For C3 crops, a default maximum light use efficiency of 2.5 g/MJ is used in the SEBAL calculation. This value agrees with international literature and is representative for total above and below ground biomass of C3 crops (Bastiaanssen and Ali, 2003). The maximum light use efficiency refers to the maximum amount of grams of net carbon assimilation (after respiration) per unit of PAR without reduction due to stress conditions.

Since the crops studied in this project are both C4 crops, the maximum light use efficiency values had to be calibrated for the specific crops. These calibrated maximum light use efficiencies were used to subsequently estimate (calibrated) actual dry biomass production with SEBAL according to the Monteith model formulations (Monteith, 1972):

$Bio = APAR(t) * \varepsilon(t)$	*(5)*

where the biomass production, Bio (kg/ha) is the result of the absorption of solar radiation (APAR) used for photosynthesis and the light use efficiency (ε) that converts energy into dry matter.

The Photosynthetic Active Radiation (PAR) corresponds to the wavelength from 0.4 to 0.7 µm that is absorbed by chlorophyll for photosynthesis of the plants. PAR describes the total amount of radiation available for photosynthesis if leaves intercept all radiation. This is a theoretically value because leaves transmit and reflect solar radiation and only a fraction of PAR will be absorbed by the canopy APAR and used for carbon assimilation. APAR can be approximated as a fraction of the Normalized Difference Vegetation Index (NDVI) as defined by Asrar *et al*. (1992).

The second component of Eq. 5 corresponds to the light use efficiency (ε) and interaction with climate conditions and environmental stress on crop growth. The light use efficiency is coupled to the stomatal aperture that is expressed into bulk surface resistance r_s. The r_s is a function of the effect of temperature and vapor pressure on stomatal aperture and the impact of soil water potential on r_s. When stomata close due to water stress or environmental conditions, it will induce lower leaf water potential that will limit expansion of guard cells and light is no longer effectively converted into dry matter because the capture of carbon is limited. The maximum light use efficiency (ε_{max}) is multiplied by the resistance in order to obtain the actual value for light use efficiency:

$\varepsilon(t) = \varepsilon_{max} * r_s(t)$	*(6)*

This results in a dynamic light use efficiency that varies with environmental or water stress conditions.

2.5.1.4.1 Calibrating biomass production and estimating above ground dry matter

The SEBAL total biomass estimates (above and below ground) were accumulated and multiplied with a fraction of 1.28 in order to compensate the maximum light use efficiency used in SEBAL of 2.5 g/MJ with a maximum light use efficiency of 3.2 g/MJ. The total dry biomass estimations were compared with above dry biomass measured for 13 sugarcane fields during the 2011/12 season. Figure 11 shows a good data correlation with an R^2 of 0.71 and a regression line fitted through the origin, with a slope of 0.83. This slope suggests still an underestimation of the SEBAL total (above and below) dry biomass for sugarcane fields. The maximum light use efficiency value for sugarcane was hence adjusted using this slope of 0.83 and a root biomass partitioning of 12% was assumed to account for below ground partitioning following Van Antwerpen (1996), when the stalk growth is triggered. In this study, the stalk biomass was triggered when the canopy cover reached 68 %. This resulted in a maximum light use efficiency of 4.5 g/MJ.

In order to evaluate the correspondence of this calibrated maximum light use efficiency value for sugarcane, a different dataset of above dry biomass (2012/13) was correlated with SEBAL above ground biomass estimations, shown in Figure 12. The data correlation improved with an R^2 of 0.73 and a slope of 0.99. This approach was hence followed to estimate sugarcane total biomass and above dry biomass for stalk growth.

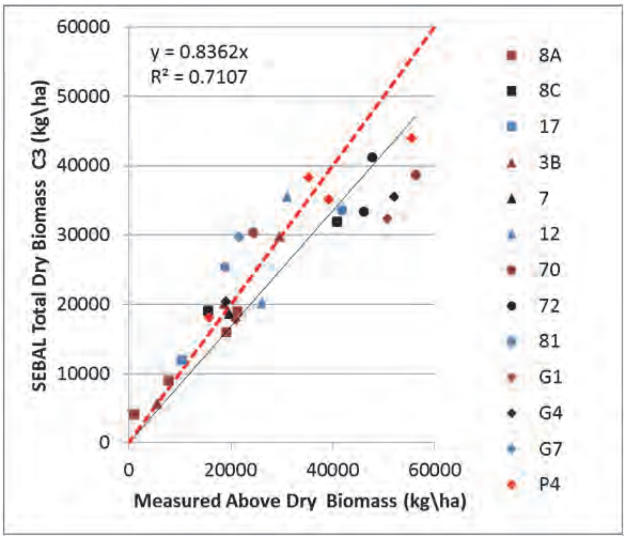


Figure 11. Correlation between SEBAL Total Dry Biomass C3 and Measured Above Dry Biomass for sugarcane

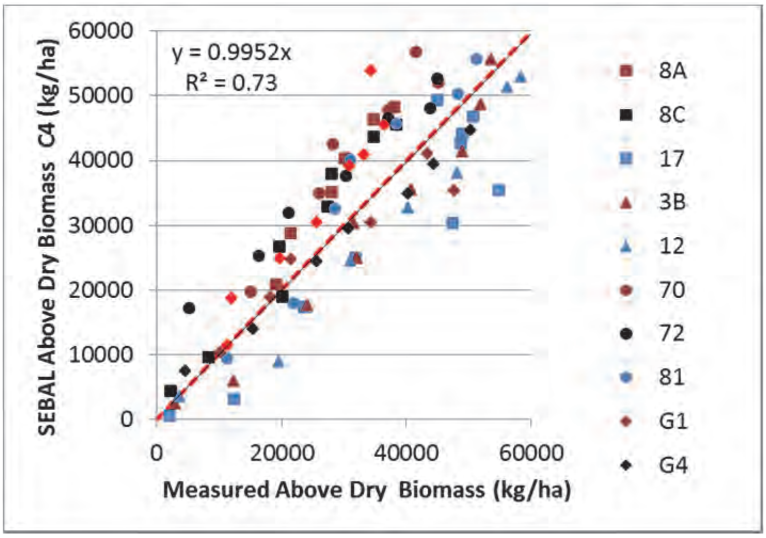


Figure 12. Correlation between SEBAL Above Dry Biomass C4 and Measured Above Dry Biomass for sugarcane

2.5.1.5 Water use efficiency

For sugarcane, the water use efficiency was expressed as the total biomass produced (kg/ha) per unit of water used (SEBAL estimated ET) (mm) (Eq. 7) but also as stalk dry mass (SDM) (yield) (kg/ha) produced per unit of water used (mm) (Eq. 8).

$$WUE_{BIO} = (BIO/ET) * 0.1 \quad (7)$$

$$WUE_{SDM} = (SDM/ET) * 0.1 \quad (8)$$

WUE_{BIO} was calculated at a weekly time step but also averaged over the growing season. Since SEBAL does not estimate yield directly, the water use efficiency (WUE_{SDM}) for the monitored fields was only determined at the end of the season once SDM at harvest and total seasonal ET estimates were available. The water use efficiency is expressed in kg/m^3.

2.5.1.6 Canopy cover and Normalised Difference Vegetation Index

SEBAL estimates canopy cover and Normalised Difference Vegetation Index (NDVI) in its intermediary steps and these parameters are also output and used. Canopy cover can be defined as the proportion of soil covered by the canopy. The canopy cover is an indicator of development of the crop during the growing season.

The NDVI provides an indication of the growth vigour of a crop or vegetation and was formulated by Tucker (1979). NDVI is calculated as the ratio of the difference in the spectral reflectance measurements acquired in the near infra-red (NIR) and red (R) range, to the sum of the Near Infra-red and red spectral reflectance estimates. Data from DMC was used in the calculation of NDVI.

$$NDVI = (NIR - R)/(NIR + R)$$

2.5.2 Data inputs

2.5.2.1 Spatial data

SEBAL requires information captured in the visible (VIS), near-infrared (NIR) and thermal infrared (TIR) range of the electromagnetic spectrum. For the sugarcane modelling, data from the Disaster Monitoring Constellation (DMC) sensor was combined with data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite and data collected by other satellites.

The DMC sensor acquires data at a 22 m spatial resolution in the visual (green, red) and near-infrared ranges. The DMC data is resampled to 30m spatial resolution. DMC does not acquire thermal information required for the SEBAL modelling and this information (land surface temperature) is taken from the MODIS satellite. MODIS thermal data is acquired at a 1 km spatial resolution. The MODIS land surface temperatures are first re-sampled to a 250 m resolution, after which a thermal sharpening tool is applied and the MODIS thermal data further down-scaled to 30 m resolution.

The DMC sensor was programmed to acquire an image covering the sugarcane study area (Figure 13) roughly every ten days over the period 1 November 2011 to 31 October 2012. A total of 43 DMC and 45 MODIS images were used over this period. For the extended period (1 November 2012 to 31 July 2013), at least one DMC image was acquired per month. The images used are described in Jarmain *et al*. (2012) and Dost *et al*. (2013).

The Digital Elevation Map (DEM) required in the SEBAL modelling was taken from the Shuttle Radar Topography Mission (SRTM).

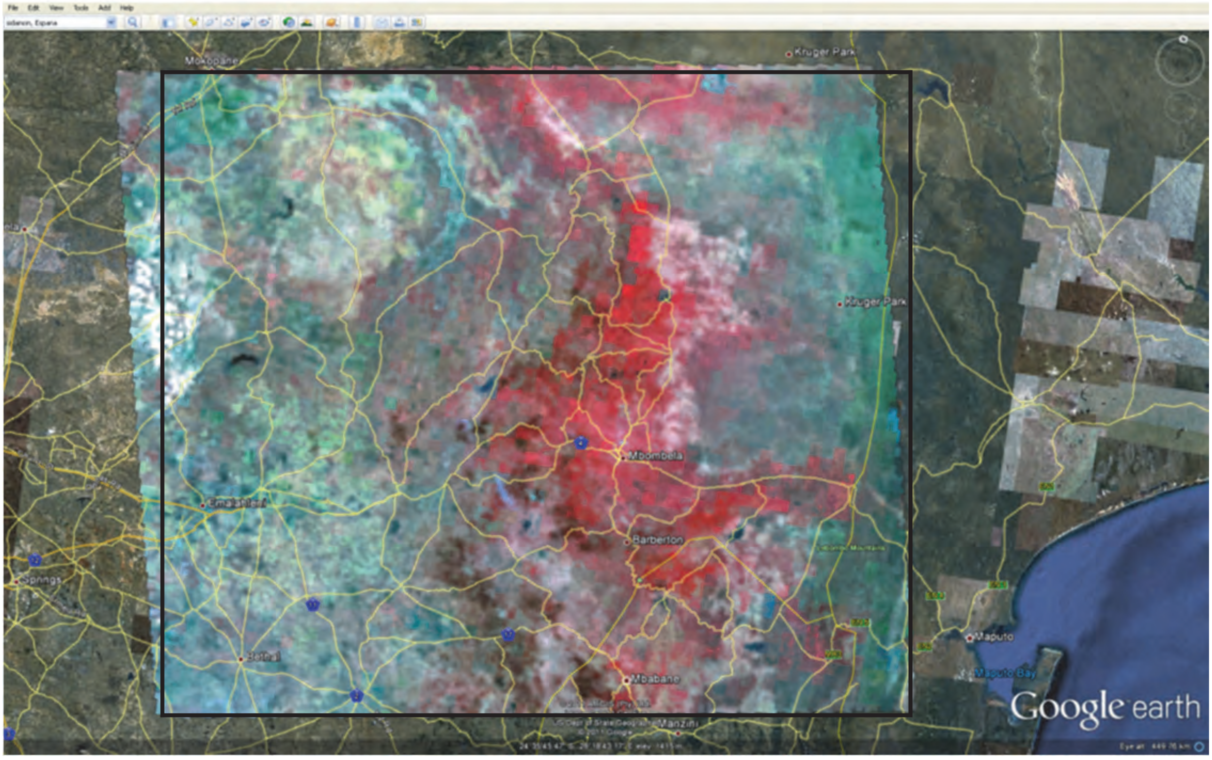


Figure 13. The extent of a DMC image acquired on 4 November 2011

2.5.2.2 *Meteorological data inputs*

SEBAL requires as input, spatially extrapolated (gridded) meteorological data in the various processing steps (Figure 10). Meteorological data (temperature, relative humidity and wind speed) was taken from nine weather stations from the NOAA meteorological stations data base (Table 6) and spatially extrapolated using the MeteoLook tool (Voogt, 2006) for the entire Incomati catchment, including the and overlapping the sugarcane study area. MeteoLook produces spatially extrapolated meteorological data at a 300 m resolution which is resampled to a 30 m spatial resolution.

Table 6. Meteorological stations in the study area used in MeteoLook to provide gridded meteorological data for the entire Incomati catchment, including and overlapping the sugarcane study area

Meteorological station	Latitude (Dd)	Longitude (Dd)	Meteorological station	Latitude (Dd)	Longitude (Dd)
Maputo/Mavalane	-25.917	32.567	Manzini/Matsapa	-26.533	31.3
Ermelo	-26.5	29.983	Witbank	-25.833	29.183
Nelspruit	-25.5	30.917	Graskop	-24.933	30.85
Kruger_Mpumalan	-25.433	31.1	Carolina	-26.067	30.117
Hoedspruit	-24.35	31.05			

2.5.2.3 *Other data used*

A spatial map outlining the most recent sugarcane production area was made available by the Mpumalanga Cane Growers Association (MPCGA) (MPCGA, 2012) and this was used to extract the spatial data from the sugarcane fields.

2.5.3 SEBAL further developments: Yield modelling

2.5.3.1 Cane yield model

Weekly biomass estimates from SEBAL used a maximum light use efficiency (ε) of 4.5 g/MJ, where ε is defined as the net biomass assimilated (after respiration) per unit of photosynthetically active radiation (0.4 to 0.7 µm) intercepted by the crop, at optimal temperature and water status. The value of ε was determined through calibration using field measurements of above ground biomass from the 13 fields and assuming a root fraction of 12 %.

To estimate cane yield, a new algorithm was developed. Weekly biomass increments (ΔTDM) as estimated by SEBAL were partitioned into aerial dry mass (ΔADM) and to stalks (ΔSDM), following the approach used in the CaneSim® and Canegro models, fully described by Singels and Bezuidenhout (2002):

$$ADMPF = ADMPF_{max}.(1 - e^{-b.TDM}) \quad (9)$$

$$\Delta ADM = \Delta TDM.ADMPF \quad (10)$$

$$\Delta SDM = \Delta ADM.SKPF \quad (11)$$

where $ADMFP_{max}$ is the maximum partition fraction of biomass to aerial biomass (in a mature crop), ADMPF and SKPF are the partition fractions for aerial dry mass and stalk dry mass respectively, b is an empirical parameter (see Table 7) and TDM is total (above-ground and below-ground) current biomass. The value of SKPF depended on the development phase (tillering or stalk growth) of the crop (Singels and Bezuidenhout, 2002; Table 7).

The start of stalk growth was predicted by accumulating a specified amount of thermal time (TT) (Table 7) from the start of the crop (Singels and Bezuidenhout, 2002). Thermal time was calculated using spatially averaged weekly maximum and minimum temperatures (T_{max}, T_{min}) and a base temperature (T_b) of 10 ˚C (TT = (T_{max} +T_{min}) – T_b and TT > 0). This version was called SEBALMC TT. A second version (SEBALMC CC) predicted the start of stalk growth when SEBAL estimates of canopy cover (CC) reached 68 % (CCskp, Table 7). This threshold value was determined by calculating the average SEBAL canopy cover at TT=1100 ^oCd for the 13 ratoon crops that were monitored.

Biomass (TDM), aerial dry mass (ADM) and stalk dry mass (SDM) were calculated by accumulating weekly increments over time. Stalk fresh mass (an industry standard known as cane yield, CY) was calculated by dividing stalk dry mass by stalk dry matter content. The latter was calculated from stalk dry mass and sucrose mass following the method of Martine and Lebret (2001).

Because SEBAL data was only available from November 2011 when the 2011/2012 crops were already well into their growing cycle, a method of initialising the accumulation of biomass components was needed. When the TT estimated start of stalk growth for a given field occurred before the start of SEBAL data, the SEBAL yield models was initialised with the cane yield, stalk dry mass and sucrose mass values simulated by the CaneSim® model on the start date of SEBAL data. When the first SEBAL CC estimate was higher than the assumed trigger level for the start of stalk growth, the CC version of SEBAL could not be run. Missing SEBAL estimates of biomass increments due to clouds (five cases affected three fields or 0.4% of the data) were replaced with CaneSim® estimates of biomass increments.

2.5.3.2 Sucrose yield model

The sucrose yield algorithm was conceived by Singels (2010) and is based on concepts published in Singels and Bezuidenhout (2002), Singels and Inman-Bamber (2011) and Singels *et al*. (2003). It accounts for:

- genetic differences in sucrose content of mature stalks,
- the fact that stalk internodes reduce their growth rate and become more mature (increasing levels of sucrose) as they age physiologically, and
- the fact that cool temperatures and mild crop water stress affect stalk growth more negatively than photosynthesis, and hence enhances sucrose accumulation in immature internodes.

A description of the algorithm follows: The number of internodes of an imaginary single big stalk is calculated using thermal time (base 10 ^{o}C). The first internode appears after 250 ^{o}Cd has accumulated since shoot emergence and subsequent internodes appear every 100 ^{o}Cd thereafter. This produces about 8 internodes when the stalk starts to grow to match the number of fully expanded leaves often observed at the time when the elongation of the stalk can be observed. Internodes are classified as ripe (high sucrose content) or green (low sucrose content) based on their physiological age. The youngest ten internodes are considered green (low sucrose content), while the rest are considered ripe (high sucrose content).

Weekly stalk dry mass increments are allocated to the green section of the stalk. The stalk dry mass of the green section is calculated by accumulated weekly stalk increments and subtracting the stalk dry mass that has ripened in the current week (stalk dry mass of internodes that moved from the green to the ripened section of the stalk). Conversely, the stalk dry mass of ripened section is calculated by accumulated stalk dry mass that has ripened in each week. The sucrose mass of the ripe section is calculated as the product of the maximum sucrose content and stalk mass. The maximum sucrose content (SUC_{max}) is defined as the sucrose content (dry mass basis) of mature internodes in the base of the stalk when subjected to cool conditions and mild water stress and is assumed to be 0.55, 0.58 and 0.60 for low, medium and high sucrose cultivars. In this study a value of 0.58 for SUCmax was used for all of the fields. The sucrose content of the green section of the stalk (SUC_{green}) is calculated as a function of recent temperature (FT) and water status (FW):

$$SUC_{green} = SUC_{max}.RVI$$	*(12)*

$$RVI = 1/28\Sigma(FT + FW)/2$$	*(13)*

$$FT = 1/\left[1 + e^{(0.32(T-25))}\right]$$	*(14)*

$$FW = \left[ET_{def} / \left(ET + ET_{def}\right)\right]^{0.5}$$	*(15)*

where RVI is an index representing the favourability of temperature (FT) and water status (FW) conditions of the last four weeks for sucrose; and T, ET and ET_{def} are SEBAL estimates of average temperature, evapotranspiration and evapotranspiration deficit for the given field. The power 0.5 term in the FW equation, reflects the enhanced effect of a mild water stress, compared to a severe stress, on sucrose accumulation. The FW factor used here replaces the FW factor in a previous version which was calculated from soil water status:

$$FW = 1 - [ASWC/(0.55\,TAM)]^{0.5}$$	*(16)*

where ASWC is available soil water content (mm) and TAM is ASWC at field capacity (mm) (see Singels *et al*., 2003 and Singels *et al*.,2012).

The sucrose mass in the green section is calculated as the product of green stalk mass and the sucrose content of the green section. The sucrose mass of the big stalk (the crop) is the sum of the sucrose mass of each section, while the sucrose content is derived by dividing sucrose mass by stalk dry mass. Sucrose content expressed on a fresh mass basis (the industry standard) was determined by dividing sucrose mass by stalk fresh mass.

The two SEBALMC models were validated using observed values of stalk dry mass as well as cane yield, sucrose yield and sucrose content recorded by the mill at final harvest. Model performance was also benchmarked against that of the stand-alone CaneSim® model. The cane yield (or stalk fresh mass) and sucrose yield model parameters are summarised in Table 7.

Table 7. List of parameters for the SEBAL driven cane and sucrose yield models

Parameter	Description	Value	Reference
TT_{emerge} (°C.d)	Thermal time from the start of a ratoon crop to emergence of primary shoots, base 10 °C	100	
TT_{skp} (°C.d)	Thermal time from shoot emergence to start of stalk growth , base 10 °C	Plant crop: 1300 Ratoon crop: 1100	Adapted from Singels and Bezuidenhout (2002)
TT_{int1} (°C.d)	Thermal time required to produce the first internode after shoot emergence, base 10 °C	250	
TT_{int} (°C.d)	Thermal time required to produce an internode after the first internode, base 10 °C	100	Adapted from Singels *et al*. (2008)
INT_{green}	Maximum number of elongating, green internodes	10	Singels and Inman-Bamber (2011)
CC_{skp} (%)	Canopy cover at the start of stalk elongation	0.68	This study
$ADMPF_{max}$	Maximum partition fraction of biomass to aerial biomass (in a mature crop)	0.88	Singels *et al*. (2008)
B	ADM partitioning extinction coefficient	0.6	Singels *et al*. (2008)
SKPF	Partition fraction of aerial dry mass to stalk mass	Tillering: 0 Stalk growth: 0.65	Singels *et al*. (2008)
SUC_{max}	Maximum sucrose content in the ripened section of stalk of a mature crop	0.58	Singels *et al*. (2008)

2.5.4 CaneSim® crop forecasting system (CCFS): Enhancing crop forecasts with remotely sensed data

2.5.4.1 Brief description of CaneSim® crop forecasting system

Forecasts of the size of the sugarcane crop are essential information for the S.A. sugar industry to optimize sugarcane production, milling and sugar selling. The CaneSim® crop forecasting system (CCFS) and daily data from approximately 70 weather and rainfall stations are used to simulate crops for each month of the milling season. Seasonal rainfall outlooks are used to generate 10 likely future daily weather sequences to simulate the future. Mean yields are calculated for homogenous climate zones, mill areas and the industry and expressed as a percentage of the yield of the previous year. This is done because simulated yields are always substantially higher than actual yields (Bezuidenhout and Singels, 2007b) because the model assumes ideal agronomic conditions including no limitations due to pests, diseases, weeds or nutrition. A forecast expressed as a relative yield allows users to apply it to their specific situation (field, farm, zone or mill supply area) in the context of the previous year yield or production. Information is disseminated to the industry on a monthly basis from November of the year preceding the harvest years, to August of the harvest year.

Two versions of CCFS is available, namely one where yield is driven primarily by transpiration ($CCFS_{ET}$, see Singels *et al*.,1998), and one where yield is driven by intercepted radiation and crop water status ($CCFS_{RAD}$, Singels and Bezuidenhout, 2002). The model has a single layer soil water balance (see Singels *et al*., 1998 for a full description) and simulates crop transpiration, evaporation from the soil, deep drainage and run-off. Crop canopy cover is calculated from thermal time (Singels and Donaldson, 2000) and crop water status (Singels *et al*., 2008). Canopy cover is used to calculate interception of solar radiation that drives potential transpiration and biomass accumulation. Actual transpiration (T) and biomass accumulation (TDM) is determined by potential rates and crop water status (SWSI), which depends on soil water status (Singels *et al*., 2010). The CCFS is fully described by Bezuidenhout and Singels (2007a; 2007b).

2.5.4.2 *Enhanced CaneSim® crop forecasting system*

CaneSim® forecasts have to rely on broad assumptions with regards to average soil and crop properties, and irrigation practices for each scenario. Remote sensing (RS) data could be used to (1) reset the current state of the crop (canopy cover, crop water relations and growth vigour) in model simulations, and (2) introduce a finer resolution to yield forecasts, effectively increasing the number of scenarios and spatial variation covered. Examples of this exist in the literature (Ines *et al*., 2013).

In this project, the aim was to determine whether the accuracy of CaneSim® crop forecasts can be improved by using remotely sensed data to reset simulated data. Specifically, to compare virtual April and December forecasts of 2012 average yields for the two homogenous climate zones in the Komati mill supply area for each harvest month (April to December) with and without weekly SEBAL estimates of canopy cover (CC), evapotranspiration (ET), crop water status, biomass growth (ΔTDM) as model input, with actual yields. A virtual April forecast means that actual weather (and available SEBAL) data for the period from the start of the crop to 15 April are used as input, with likely future daily weather sequences used for the remainder of the growing season. It is called virtual because the actual run took place much later and is therefore not a true forecast.

The following remotely sensed data variables were used to replace CaneSim® simulated values:

$$CC = CC_{SEBAL} \quad (17)$$

$$T = ET_{SEBAL} - E_{soil} \quad (18)$$

$$SWSI = ET_{SEBAL}/(ET_{SEBAL} + ETdef_{SEBAL}) \quad (19)$$

$$\Delta TDM = \Delta TDM_{SEBAL} \quad (20)$$

where CC is daily canopy cover, T is daily transpiration, SWSI is the soil water satisfaction index and ΔTDM is daily increment in total dry biomass as used in CaneSim® simulations, CC_{SEBAL} is the weekly average canopy cover estimated from satellite imagery, ET_{SEBAL} is the SEBAL estimated weekly average daily evapotranspiration, E_{soil} is CaneSim® estimate of daily evaporation from the soil surface, $ET_{defSEBAL}$ is the SEBAL estimate of weekly average daily ET deficit and ΔTDM_{SEBAL} is the SEBAL estimate of weekly average daily biomass increment.

SEBAL data for the period (November 2011 to December 2012) for each field in the Komati mill supply area were aggregated by averaging weekly values for fields with the same harvest month and in the same zone. This resulted in a table with data for two zones by nine harvest months (Apr 2012 to Dec 2012) for each week from November 2011 to the harvest month in 2012. Fields smaller than 3 ha were excluded from the analysis because reliable remote sensing data were not available for fields smaller than 3 ha.

Predicted cane yield from the two versions of the CaneSim® model using SEBAL input data, were compared to yields simulated only with weather data, as well as with actual yields. Actual yield data were obtained from the TSB database on 27 March 2013. Data from fields that were less than 3 ha in size and fields that were harvested outside of the period from 1 April to 31 December were excluded when calculating the average yield for each zone and harvest month as the CCFS only forecasted yields for crops harvested within this period. The total area harvested on fields that qualified for the analysis was 17588 ha, out of a total of 18559 ha in the TSB database.

The accuracy of forecasts was quantified by calculating the average difference between forecasted and actual yields over zones and harvest months.

2.5.5 Freely available spatial data products: MOD16

In recent years, the freely available MOD16 evapotranspiration data product has attracted attention in South Africa and was briefly investigated in this project. The MOD16 products are regular 1 km^2 global land surface datasets of evapotranspiration (ET), latent heat flux (LE), potential ET (PET) and potential LE (PLE). The products are available for vegetated land areas at 8-day, monthly and annual intervals (Mu *et al*. 2007, 2011). MOD16 products uses the MODIS global landcover product (MOD12Q1), a daily meteorological reanalysis data set from NASA's Global Modelling and Assimilation Office as well as MODIS biophysical parameters as input into the Penman-Monteith equation. The biophysical parameters include albedo from MODIS surface reflectance product (MOD43C1), Leaf Area Index (LAI) product (MOD15A2) and Enhanced Vegetation Index (EVI) product (MOD13A2 EVI). The MOD16 data product (mm/month) (Mu *et al*. 2011) is produced in 10-degree Sinusoidal HDFEOS tiles. Data are produced and posted periodically only and not in near-real time. The 8-day ET product is the sum of ET (in mm) during the 8-days.

For sugarcane, data was downloaded from the MOD16 download site (ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products/MOD16/) for the period 8 October 2011 to 26 December 2012. The study area was covered by a single tile (h20v11). The MOD16 data was converted into regular 1km^2 grid cells and projected into the same projection as the SEBAL data (UTM WGS84 36S) using the MODIS re-projection tool (MRT). Non-vegetated pixels (marked as invalid in the MOD16 product) were set to No data. The coordinates of the field sampling points were then used to extract the ET data (in mm/8days). The MOD16 data was converted into daily ET estimates to compare against the SEBAL ET estimates.

CHAPTER 3: WATER USE EFFICIENCY OF IRRIGATED SUGARCANE - RESEARCH FINDINGS AND APPLICATIONS

3.1 INTRODUCTION

In this section the accuracy of the data sets used and produced for sugarcane will be discussed and the seasonal estimates for sugarcane summarised. The:

- MyCaneSim® model improvements are assessed,
- SEBAL spatial estimates compared with field observations and estimations from well-established models from South Africa,
- Low resolution MOD16 estimates compared with high resolution SEBAL ET estimates,
- Improvements ito yield forecasting with the enhanced CaneSim® Crop Forecasting System (CCFS) model assessed, and
- Seasonal data related to water and crop growth summarised for sugarcane.

3.2 ASSESSING QUALITY OF IRRIGATION DATA INFERRED IN THE IMPROVED MYCANESIM® SYSTEM

Results for inferring irrigation are shown in Table 8 and Table 9. Seasonal irrigation totals (inferred irrigation total for periods with measured ASWC data, plus simulated irrigation totals for periods without measured ASWC data) for 2012 were mostly within the typical range (Olivier and Singels, 2004), while there was mostly a very good match between yields simulated with inferred irrigation (Y_{irr}) and yield simulated with corrected ASWC (Y_{swc}). The exceptions were fields 17, G7, 3B, and 72, where Y_{irr} was substantially lower (more than 20%) than Y_{swc}. This implies that inferred irrigation totals and/or the number of events may have been underestimated. In the case of field 17 there were two instances where the measured ASWC increased significantly on consecutive days without rainfall being measured at associated weather station. This is an indication that the farmer irrigated on consecutive days, an occurrence that was not catered for in the algorithm. In the case of fields G7 and 72 the underestimation may have been caused by an overestimation of canopy interception losses of frequent, small irrigations applied by centre-pivot (5 mm for a full canopy crop).

Inferred seasonal irrigation totals in 2013 was mostly lower than in 2012, presumably because rainfall was generally much higher. There was a good match between Yirr and Y_{SWC} except for fields G1, 3B and 72, where Y_{IRR} was more than 20% lower than $Y_{SWC.}$ Again this implies that inferred irrigation totals and/or the number of events may have been underestimated.

It is acknowledged that the algorithm developed for inferring irrigation could not be tested with appropriate data and that its output should be treated with caution. The study suggest that it may be very difficult to infer historic irrigation events reliably from soil water status records and that measurements with flow meters or rain gauges are needed for accurate records.

Table 8. **Inferred irrigation for each field for the 2011 /2012 growing season. Irrigation totals as inferred from soil water content (ASWC) records, totals as simulated for periods where ASWC data were not available, and the sum of these two totals.**

					Irrigation					Simulated yields	
Farm code	Field name	Days with ASWC data (d)	Season length (d)	Seasonal rainfall total (mm)	Design amount (mm/event)	Inferred events	Inferred total[14] (mm)	Simulated total[15] (mm)	Seasonal total[16] (mm)	Y_{irr}[17] (t/ha)	Y_{swc}[18] (t/ha)
A	8A	198	334	635	7	103	721	133	854	109	108
A	8C	230	333	635	7	92	644	140	784	102	100
B	17	257	352	552	24	6	144	0	144	35	67
C	G1	211	369	557	7	99	693	182	875	122	121
C	G4	88	358	557	7	26	182	700	882	119	119
C	G7	110	331	550	12	3	36	876	912	81	110
C	P4	112	427	1044	7	48	336	686	1022	154	157
D	3B	224	405	564	6	42	252	276	528	79	120
D	7	217	343	557	48	6	288	240	528	82	82
E	12	226	366	624	8	42	336	176	512	81	99
F	70	225	368	627	6	86	516	300	816	113	120
F	72	340	410	838	15	61	915	0	915	119	153
F	81	325	370	627	6	166	996	0	996	112	121

[14] Irrigation total as inferred from measured soil water data
[15] Irrigation total as inferred from simulated irrigation for periods with no measured soil water data
[16] Irrigation total inferred for the entire growing season (sum of 1 and 2)
[17] Yield simulated using inferred irrigation (Y_{irr})
[18] Yield simulated using corrected ASWC (Y_{swc})

Table 9. Inferred irrigation for each field for the 2012/2013 growing season. Irrigation totals as inferred from soil water content (ASWC) records, totals as simulated for periods where ASWC data were not available, and the sum of these two totals.

					Irrigation					Simulated yields	
Farm code	Field name	Days with ASWC data (d)	Season length (d)	Seasonal rainfall total (mm)	Design amount (mm/event)	Inferred events	Inferred total[19] (mm)	Simulated total[20] (mm)	Seasonal total[21] (mm)	Y_{irr}[22] (t/ha)	Y_{swc}[23] (t/ha)
A	8A	239	377	915	7	96	672	182	854	113	113
A	8C	326	375	916	7	111	777	119	896	108	113
B	17	232	433	1387	9	34	306	234	540	72	72
C	G1	267	378	945	7	30	210	63	273	86	112
C	G4	280	372	945	7	94	658	105	763	118	121
C	P4	260	347	630	7	81	567	21	588	102	123
D	3B	354	489	1112	6	49	294	48	342	76	127
E	12	267	371	947	8	38	304	96	400	86	84
F	70	366	400	825	6	89	534	30	564	72	122
F	72	294	320	620	15	45	675	60	735	91	110
F	81	365	396	825	6	141	846	54	900	109	128

[19] Irrigation total as inferred from measured soil water data
[20] Irrigation total as inferred from simulated irrigation for periods with no measured soil water data
[21] Irrigation total inferred for the entire growing season (sum of 1 and 2)
[22] Yield simulated using inferred irrigation (Y_{irr})
[23] Yield simulated using corrected ASWC (Y_{swc})

3.3 VALIDATION OF FIELD ESTIMATES OF ET, ET_{DEF}, BIOMASS AND YIELD ESTIMATES OF SUGARCANE

Weekly estimates from SEBAL, MyCaneSim® and SAPWAT (where available) of CC, ET, ADM, SDM and cane yield were compared to observed values (Figure 14, Figure 15). For SEBAL, the total dry matter (TDM) estimates had to be compared to ADM measurements, as ADM estimates were not available from SEBAL and TDM was not measured. Also, SEBAL TDM estimates were derived by accumulating weekly estimates from the first measurement and setting the starting value equal to the measured value. Goodness of fit was quantified using the coefficient of determination and the slope and intercept of linear regressions between simulated and observed values.

Weekly estimates of ET deficit (ET_{def}, defined as the difference between potential and actual evapotranspiration) were compared to the number of stress days per week (defined as a day when the available soil water content, as determined from soil water sensor readings, was below 50% of capacity) (Figure 14).

Simulated and actual yields for the different fields at harvest are shown in Table 10 and Table 11. A detailed comparison of the observations and SEBAL estimates of the energy balance and ET data at sub-weekly intervals is given in Appendix I.

Figure 14 example of the validation of CaneSim® and SEBAL estimates of canopy cover (CC), evapotranspiration (ET), ET deficit (ET_{def}) and biomass against field observations. Except for ET where only field G1 was monitored, this validation was done for all fields. The ET data from SAPWAT is also shown here. There was good agreement between estimated and observed CC for the 2011/12 season, while in the 2012/13 season CaneSim® overestimated and SEBAL underestimated CC. The under estimation of CC by SEBAL is due to long periods of patched or inferred data when cloudiness prevented the calculation of CC from updated NDVI data or when data was unavailable due to administrative reasons.

Despite the difference in CC estimates, SEBAL and CaneSim® estimates of ET for field G1 were very similar for 2011/12 and both overestimated ET determined by the surface renewal (SR) method by about 4 to 7 mm/week on average. CaneSim® estimates were much lower than SEBAL estimates and SR measurements in the very young 2012/13 crop, but as canopy cover reached about 50%, the estimates and measurements compared well. The SAPWAT ET estimates do not show the seasonal variation due to changes in climatic conditions (Figure 14). Except for the cloudy and rainy days, SAPWAT ET was generally lower than the SEBAL estimates. Mid-summer ET estimates with SAPWAT were substantially lower than the other estimates.

ET_{def} estimates compared reasonably well with the stress index as determined from soil water sensor measurements, as can be seen from the spikes in Figure 24, mostly matching periods when the stress index was 100%. SEBAL did not indicate significant ET_{def} during the first (Jan 2012) and third (August 2013) stress periods.

Model estimates of biomass compared very well to adjusted observed field values (Figure 14), although it should be noted that SEBAL TDM is compared with CaneSim® and observed ADM values. Figure 15 shows comparison of yield estimates with observed values for field G1. Cane yield, SDM, sucrose yield and sucrose content were estimated very well by all models in 2011/12, while CaneSim® estimates in 2012/13 was also very accurate. Both SEBALMC models underestimated yields in 2012/13.

A number of aspects to note from the model validation for other fields (Appendix II) were:

- There were a large proportion of patched RS canopy cover data that may have affected SEBAL estimates for other variables as well. The lack of RS data for a period was due to the delay in getting a contract for the supply of the spatial data.

- The CaneSim® model with measured soil water data as input, simulated severe water stress for field 17 from about August 2013 until harvest. This was not reflected in SEBAL calculations, resulting in large differences in yield estimates between the two methods (69 t/ha for CaneSim® *vs*. 125 t/ha for SEBALMC TT). The SEBAL estimate was much closer to the observed value of 108 t/ha. This demonstrates the advantage of using RS technology over point based models to estimate field average yields. It is suspected that the bigger portion of the field was not treated the same than the monitored area, or that the probe gave incorrect data.

- The SEBALMC CC yield model performed poorly for 2013 and was much less accurate than the SEBALMC TT yield model. The reason is that the estimated start of stalk elongation, based on the canopy cover threshold of 68%, was too late because of the large amount of patched RS canopy cover data.

In Figure 16 model estimates of biomass for all fields are compared to field measurements. It should be noted that SEBAL TDM values are compared with observed ADM values. Theoretically SEBAL TDM estimates should be higher than observed ADM values to account for the root fraction that is not included the observed values. This difference should be more pronounced in young crops with relatively low biomass, as these have much larger root fractions than older crops with relatively high biomass. This is indeed the case as the data shows that low values are overestimated more than high values. Forcing the regression through a zero origin results in a slope of 1.15, which suggest an average root fraction of 15% which compares well with documented root fraction of 12% in mature crops (Singels and Bezuidenhout, 2002).

The CaneSim® model tended to overestimate low values and under estimate high values of aboveground biomass and simulated and observed values were not as strongly correlated as was the case for SEBAL. It can be concluded that SEBAL algorithm with a combination remotely sensed and weather data, produce more reliable estimates of biomass than the CaneSim® model with weather and soil water data as input.

Figure 17 shows how well models were able to estimate SDM. The SEBALMC TT model performed the best, explaining 82% of the variation in observed values. All models tended to overestimate low values and under estimate high values.

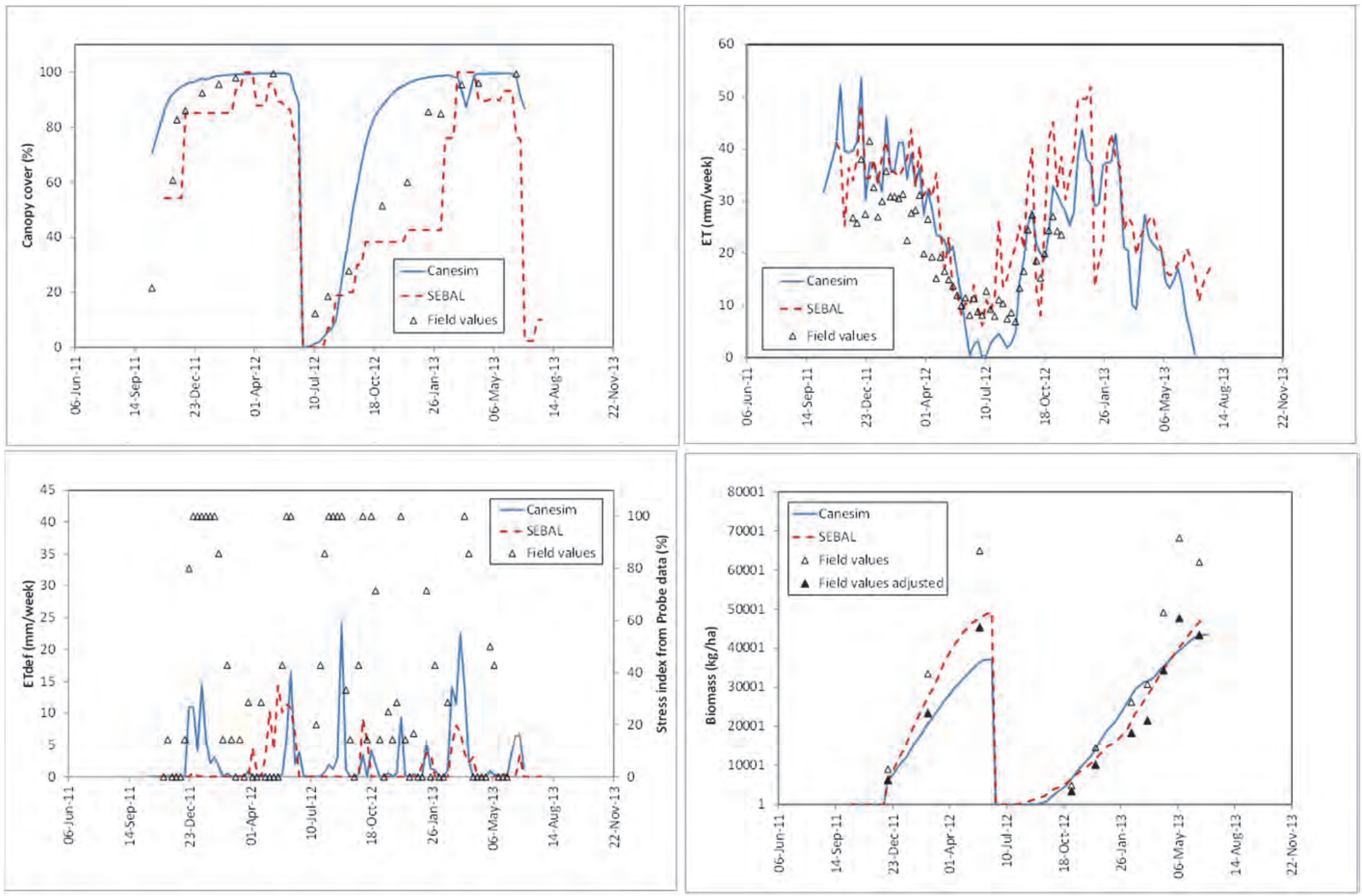


Figure 14. Time series of simulated (SEBAL, CaneSim®) and observed canopy cover, evapotranspiration (ET), evapotranspiration deficit (ET_{def}) and biomass for field G1 for both seasons

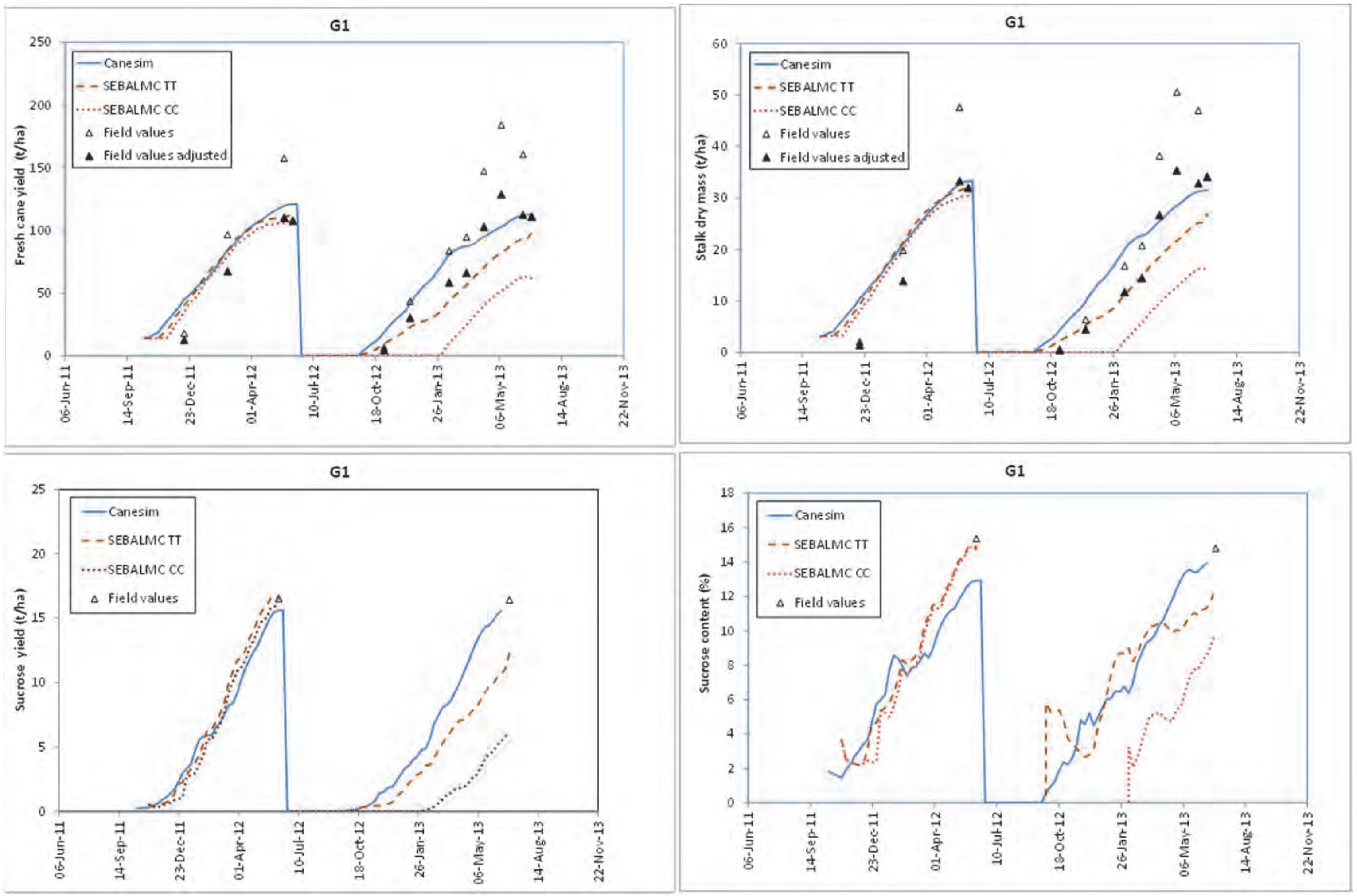


Figure 15. Time series of fresh and dry stalk mass, stalk sucrose mass and sucrose content simulated by two SEBALMC models and the CaneSim® model, compared to values measured in the field G1 for both seasons. Raw field data (open symbols) were adjusted to account for spatial within-field variation (closed symbols).

Table 10. Simulated and observed yield and quality data, and cropping details for the various fields for the 2011/12 season.

			Chemical Ripening		Cane yield (t/ha)				Sucrose yield (t/ha)				Sucrose content (% fresh mass basis)			
Farm code	Field name	Var[24, 25]	Application date	Chemical	Obs[26]	MC[27]	SBL TT[28]	SBL CC[29]	Obs	MC	SBL TT	SBL CC	Obs	MC	SBL TT	SBL CC
A	8A	N25	08/05/2012	fluazifop-p-butyl	88.15	109.45	91.59	86.94	12.32	15.22	13.35	12.55	13.98	13.91	14.57	14.44
A	8C	N25	08/05/2012	fluazifop-p-butyl	82.87	99.43	90.93	85.99	11.19	12.79	12.96	12.11	13.60	12.87	14.24	14.08
B	17	N25	None		69.44	54.96	73.29	60.47	9.96	6.12	10.93	8.75	14.35	11.14	14.89	14.43
C	G1	N19	19/03/2012 22/07/2012	ethephon; fluazifop-p-butyl	107.64	120.86	112.02	107.36	16.53	15.61	16.52	15.72	15.36	12.92	14.81	14.71
C	G4	N19	19/03/2012; 23/04/2012	ethephon; fluazifop-p-butyl	125.34	118.86	112.31	106.66	19.23	15.41	16.86	15.89	15.32	12.97	15.04	14.93
C	P4	N32	22/07/2012 26/08/2012	ethephon; fluazifop-p-butyl	115.34	153.58	148.09	160.62	15.38	21.30	20.69	22.82	13.33	13.87	13.96	14.20
C	G7	N14	11/04/2012; 16/05/2012		103.58	109.53	114.8	114.8	14.95	15.21	17.26	17.26	14.43	13.89	15.00	15.00
D	7	N19	None		79.07	108.52	83.9	79.56	11.27	13.50	12.13	11.39	14.15	13.44	14.48	14.34
D	3B	N19	None		79.90	125.06	98.7	93.21	12.42	15.87	18.28	14.04	15.54	12.69	15.44	15.14
E	12	N32	13/06/2012	ethephon; fluazifop-p-butyl	102.10	97.27	109.64	101.84	14.93	13.51	15.09	13.76	14.62	13.88	13.86	13.86
F	70	N36	27/02/2012; 29/03/2012	ethephon; fluazifop-p-butyl	113.62	117.41	117.81	117.81	17.93	13.28	18.28	18.28	15.78	11.31	15.44	15.44
F	72	N23	Flowered		141.83	151.58	126.7	131.86	18.44	20.83	20.05	21.06	13.00	13.74	15.73	15.95
F	81	N36	27/02/2012; 29/03/2012	ethephon; fluazifop-p-butyl	111.58	120.92	109.34	109.34	17.18	14.75	16.62	16.62	15.39	12.19	15.22	15.22

1

Table 11. Simulated and observed yield and quality data, and cropping details for the various fields for the 2012/13 season.

[24] Sucrose content ratings: N19, N32 and N36 - 6, N23 – 4; N14 and N25 – 2 (based on SASRI information sheets: 1 is very low, 7 is very high)
[25] Var refers to Sugarcane Variety
[26] Obs refers to observed values
[27] MC refers to CaneSim simulated values
[28] SBL TT refers to SEBALMC TT simulated values
[29] SBL CC refers to SEBALMC CC simulated values

			Chemical Ripening		Cane yield (t/ha)				Sucrose yield (t/ha)				Sucrose content (% fresh mass basis)			
Farm code	Field name	Var[30], [31]	Application date	Chemical	Obs[32]	MC[33]	SBL TT[34]	SBL CC[35]	Obs	MC	SBL TT	SBL CC	Obs	MC	SBL TT	SBL CC
A	8A	N25	12/May/2013	fluazifop-p-butyl	99.54	112.58	111.93	72.6	14.10	15.5	15.24	8.53	14.16	13.77	13.58	11.7
A	8C	N25	6/May/2013	fluazifop-p-butyl	94.53	112.80	103.79	70.27	13.20	15.9	14.08	8.37	13.96	14.10	13.53	11.85
B	17	N25			108.92	69.44	125.58	127.15	16.12	8.3	19.14?	19.41	14.80	11.46	15.31	15.43
C	G1	N19	28/Mar/2013 9/May/2013	etherel fluazifop-p-butyl	110.92	112.33	98.34	61.96	16.41	15.7	12.30	6.10	14.80	13.98	12.5	9.82
C	G4	N19	10/Sep/2013 15/Oct/2013	etherel fluazifop-p-butyl	138.00	120.74	104.28	47.39	20.31	17.2	13.60	3.90	14.72	14.25	13.04	8.2
C	P4	N32	31/Mar/2013 28/Apr/2013	etherel fluazifop-p-butyl	103.77	123.09	120.33	135.00	13.84	15.2	18.38	21.60	13.34	12.36	15.13	15.39
D	3B	N19	01/Sep/2013	fluazifop-p-butyl	98.43	126.78	137.98	129.61	12.68	17.4	20.56	19.13	14.76	13.73	14.92	14.79
E	12	N32	06/Jun/2013	fluazifop-p-butyl	101.24	83.83	118.41	11.29	14.26	11	16.73	15.51	14.09	13.14	13.94	13.75
F	70	N36	25/Mar/2013; 01/May/2013	ethephon; fluazifop-p-butyl	116.46	122.27	132.81	120.91	17.65	17.4	18.76	16.73	15.16	14.25	14.12	13.83
F	72	N23	05/Aug/2013	fluazifop-p-	117.21	104.75	136.34	113.61	17.41	14.2	16.61	12.73	14.86	12.92	12.11	11.12

[30] Sucrose content ratings: N19, N32 and N36 - 6, N23 – 4; N14 and N25 – 2 (based on SASRI information sheets: 1 is very low, 7 is very high)
[31] Var refers to sugarcane variety
[32] Obs refers to observed values
[33] MC refers to CaneSim simulated values
[34] SBL TT refers to SEBALMC TT simulated values
[35] SBL CC refers to SEBALMC CC simulated values

			Chemical Ripening		Cane yield (t/ha)				Sucrose yield (t/ha)				Sucrose content (% fresh mass basis)			
Farm code	Field name	Var[30], [31]	Application date	Chemical	Obs[32]	MC[33]	SBL TT[34]	SBL CC[35]	Obs	MC	SBL TT	SBL CC	Obs	MC	SBL TT	SBL CC
				butyl												
F	81	N36	06/Mar/2013; 6/Apr/2013	ethephon; fluazifop-p-butyl	121.28	127.68	130.41	120.41	14.80	18.2	17.96	16.25	14.80	14.25	13.76	13.49

Validation results are summarized in Table 12, firstly based on data from 2011/12, which was used to determine the LUE parameter in the SEBAL model and to initialize cumulative biomass estimates, and secondly the data from both seasons are shown. The main features are:

- SEBAL estimates of CC were more accurate than CaneSim® estimates. The CaneSim® model overestimated partial canopy cover.
- SEBAL estimates of ET for field G1 exceeded SR estimates in 2011/12 by about 7 mm/week. This overestimation reduced to 2.6 mm/week if data from both seasons were considered. CaneSim® estimates in 2011/12 were also higher (by about 10%) than SR estimates. Considering both seasons' data, it seems that CaneSim® underestimated low values (young crops with little canopy cover) and overestimated high values. This may point to a weak simulation of evaporation from the soil.
- For 2011/12 both models overestimated low biomass values, while high values were estimated reasonably well. Theoretically SEBAL TDM estimates should be higher than observed ADM to account for the root fraction that is not included the observed values. This was in fact the case as was demonstrated by a slope of 1.21 for a linear regression forced through an origin of zero. The overestimate for small crops suggest that crop partitions more to roots than older crops, which is generally accepted (Singels and Bezuidenhout, 2002). Goodness of fit (as quantified by R^2) for both models was highly acceptable. When data from both seasons are considered, both models performed remarkably well. The 15% overestimation of SEBAL is acceptable as this represents the root fraction that was not included in observations.
- The SEBALMC models performed marginally better than the CaneSim® model in simulating SDM in 2011/12 (86 *vs*. 80% of observed variation explained). Estimates of cane yield (CY) and sucrose yield (SY) at harvest for 2011/12 were not as good as SDM estimates. Again the SEBAL estimates were more accurate than CaneSim® estimates, particularly for SY estimates. The results for 2011/12 suggest that a model based on remotely sensed crop reflectance and weather data performed as well as or slightly better than a model driven with weather and soil water data.
- When the data for both seasons are considered, both models performed well in predicting SDM, but performed very poorly in predicting CY and SY at harvest.

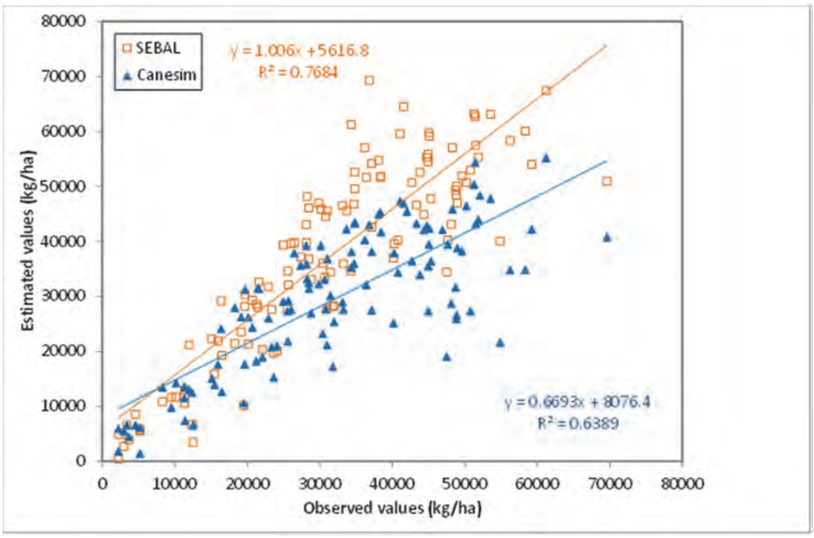


Figure 16. CaneSim® estimates of aboveground dry biomass and SEBAL estimates of total dry biomass compared to observed values of aboveground dry biomass (adjusted) for both seasons

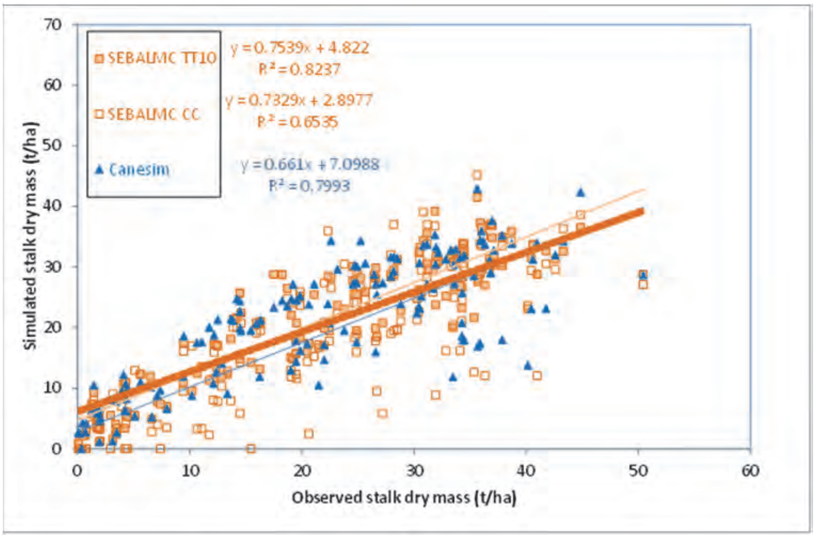


Figure 17. CaneSim® and SEBALMC estimates of stalk dry mass compared to observed values for both seasons. Best fit linear regression details are given for each model.

Table 12. Summary of validation results for all fields for 2011/2012 only and for both seasons pooled. The goodness of fit of is quantified with the slope and intercept of the linear regression between simulated and observed values, as well as the coefficient of determination (R^2). The number of data comparisons is also given (n). The first biomass observation for each field was used to initialise the model and was therefore excluded from the validation.

	SEBAL				CaneSim®		
Variable	**Slope**	**Intercept**	**R^2**	**n**	**Slope**	**Intercept**	**R^2**
2011/12							
Canopy cover (%)	1.02	-9.75	0.543	93	0.39	60.6	0.687
ET (mm/week)	1.05	4.9	0.721	29	1.21	1.1	0.747
Biomass (t/ha)	0.84	14.6	0.783	24	0.64	12.2	0.728
Stalk dry mass (t/ha)[1]	0.75 (0.79)	6.4 (5.2)	0.864 (0.858)	51	0.66	7.1	0.799
Cane yield at harvest (t/ha)[1]	0.76 (0.95)	29.2 (7.2)	0.668 (0.627)	13	0.86	27.9	0.506
Sucrose yield at harvest (t/ha)	0.79 (0.97)	4.1 (1.1)	0.677 0.571	13	0.67	5.0	0.302
2011/12 and 2012/13 pooled							
Canopy cover (%)	1.01	-10.5	0.774	196	0.86	17.6	0.768
ET (mm/week)	1.31	2.63	0.781	51	1.35	-3.3	0.836
Biomass (t/ha)	1.01	5.6	0.768	116	0.67	8.1	0.6389
Stalk dry mass (t/ha)[1]	0.75 (0.73)	4.82 (2.89)	0.824 (0.653)	151	0.66	7.1	0.799
Cane yield at harvest (t/ha)[1]	0.64 (0.53)	45.4 (46.4)	0.395 (0.118)	23	0.65	44.1	0.275
Sucrose yield at harvest (t/ha)	0.41 (0.23)	9.8 (10.9)	0.174 0.016	23	.47	7.89	0.139

[1] SEBALMC versions: SEBALMC TT and SEBALMC CC in brackets

3.4 COARSE RESOLUTION ESTIMATION WITH MOD16

Since the capture periods for MOD16 ET and SEBAL products were different, the 8 day values for MOD16 were converted to an equivalent 7 day value as extracted for SEBAL, but also into a daily ET values. Figure 28 shows the MOD16 ET data per pixel for week 15 February 2012 in relation to the SEBAL data at the sampling points for the same period with sugar cane field boundaries overlaid. For example the MOD16 pixel containing fields G1 and G4, had a weekly ET of 36.4 mm, although the overlapping SEBAL ET pixels showed variations ranging between 25.1 and 40 mm/week.

Also note for example that field G1 (Figure 18) was split over two MOD16 pixels, with very different weekly estimates of 26.2 mm/week (left part of block) and 36.4 mm/week (right part of block). Hence field G4 (fully contained in one pixel) was selected for a comparison between the daily estimates of ET derived from the MOD16, CaneSim® and SEBAL (Figure 19). The MOD16 estimates were substantially lower than the other estimates from November to December 2011 and again from August to December 2012. Surprisingly the estimates from mid-summer (January 2012) to winter (June 2012) compared well with the SEBAL and CaneSim® estimates.

The discrepancies between the MOD16 and other estimates could be attributed to the incorrect land cover assumed in the MOD16 simulations. The MOD12 data available from 2009 shows that the area discussed above is classified as woody savannas and savannas, rather than as cropland. But the differences will be largely related to the heterogeneity of the sugarcane fields, for example fields will be included representing different growing stages.

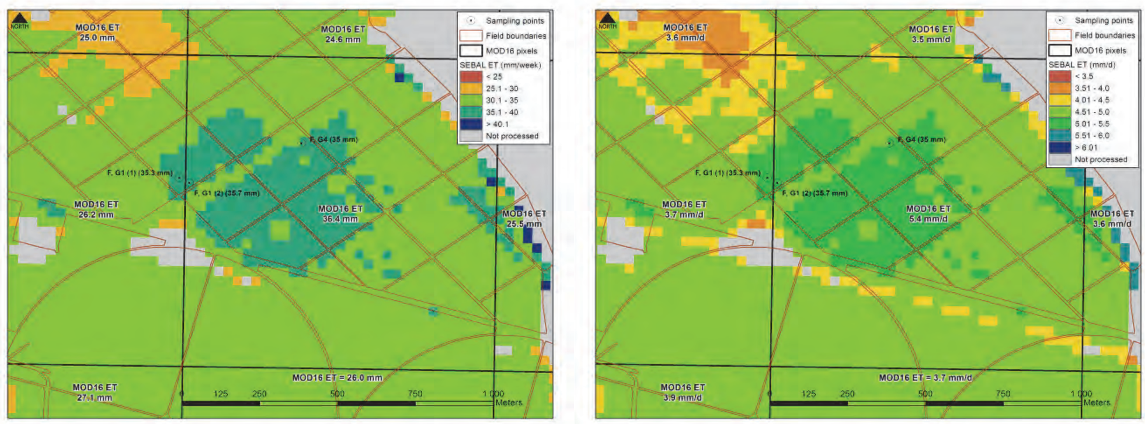


Figure 18. Comparison of ET from MOD16 (1kmx1km) adjusted to a week and SEBAL weekly ET (30mx30m) for the week ending 15 February 2014. MOD16 values are shown for each 1km pixel.

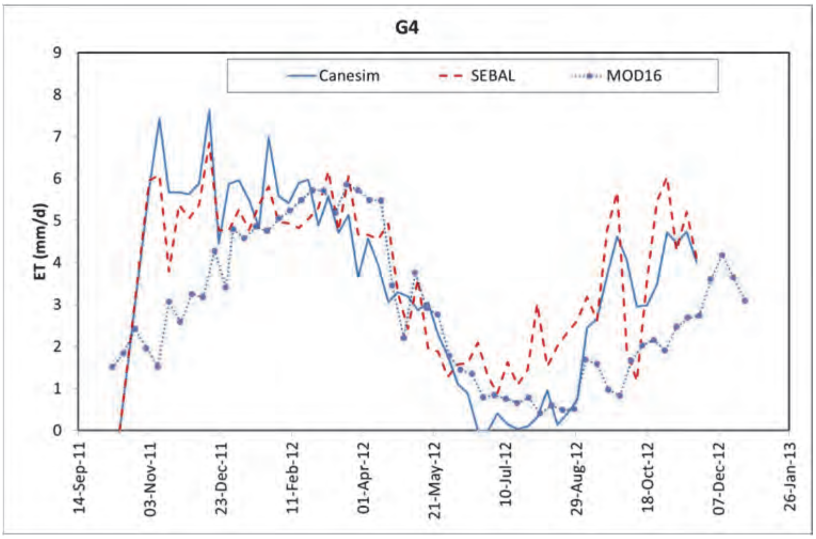


Figure 19. Comparison of daily ET estimates derived from the MOD16, CaneSim® and SEBAL data, for field G4

3.5 ENHANCED SUGARCANE FORECASTS USING REMOTELY SENSED DATA USED IN THE CANESIM® CROP FORECASTING SYSTEM

Actual yields achieved in the Komati mill supply area in 2011/12 are displayed in Figure 20. Huge variation existed and yield in zone 8 was generally much lower than in zone 1. Yields in zone 8 were low because of widespread problems on small-scale farms with respect to irrigation systems and water supply.

From a crop forecasting point of view the challenge is to account for the effects of suboptimal water supply and irrigation practices, suboptimal agronomic conditions (e.g. poor crop stand) and soil limitations. The CaneSim® crop forecasting (CCFS) only accounts for climatic conditions and regional water supply information. The hypothesis tested was that the accuracy of forecasts can be improved by using remotely sensed data and the SEBAL algorithm to enhance the weather-based CaneSim® crop forecasts.

Forecast accuracy for the April and December forecasts are summarized in Table 13 and Table 14.

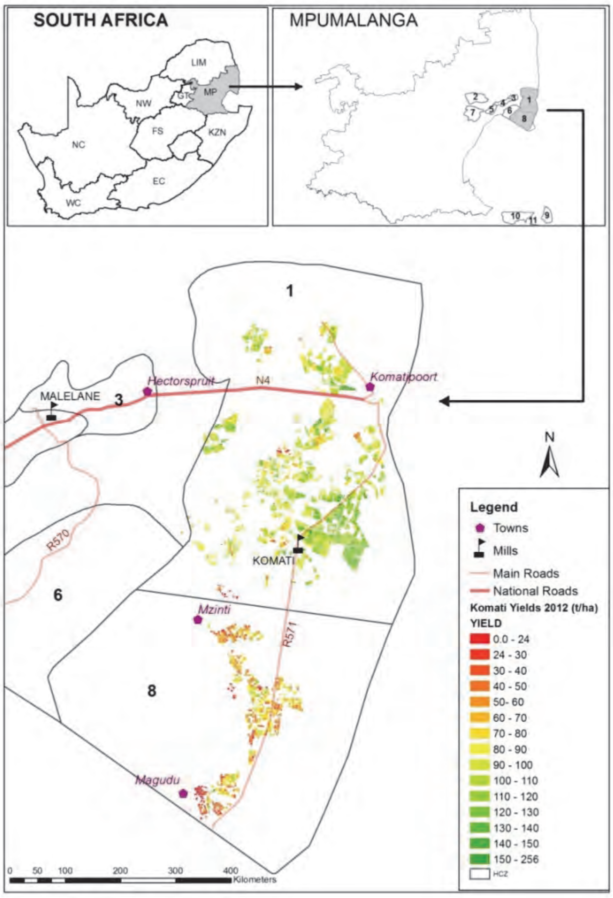


Figure 20. Map showing 2012 cane yield for fields in two homogenous climate zones (1 and 8) in the Komati mill supply area

The $CCFS_{RAD}$ model generally performed better that the $CCFS_{ET}$ model, similar to the findings of Sithole *et al*. (2010). This is because yield in fully irrigation sugarcane production scenarios are driven more by radiation than by water supply. December forecasts are obviously more accurate than April forecasts, because more actual weather (as opposed to expected weather data) and SEBAL data were available for the simulation. The best improvement in forecasts was obtained by forcing the $CCFS_{RAD}$ with remote sensing CC data, followed by $CCFS_{RAD}$ forced with SEBAL TDM data and then SEBAL ET_{def} data. Forcing the $CCFS_{RAD}$ model with SEBAL ET data performed poorly because lower ET values caused reduced water stress and increased yields, compared to CaneSim® simulations and reality.

For the $CCFS_{ET}$ forecasts the best results were obtained by forcing the model with canopy cover and ET data (Table 13).

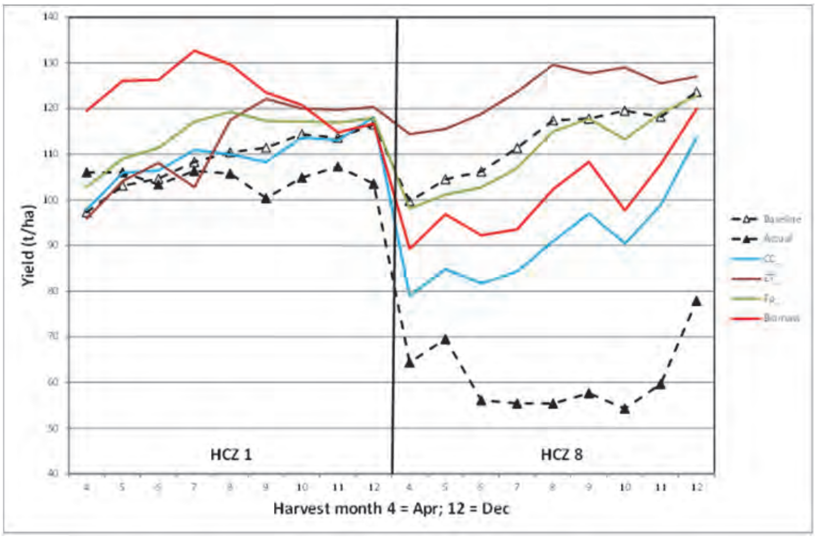
Table 13. The mean difference between forecasted and actual yields expressed as a percentage, for two versions of CCFS (RAD and ET) forced by remotely sensed canopy cover (CC), evapotranspiration (ET), evapotranspiration deficit (ET_{def}) and biomass (TDM) data. The baseline refers to stand-alone CCFS forecasts based on weather data only.

Forecast month:	April 2012		December 2012	
CCFS version:	RAD	ET	RAD	ET
RS forcing				
Baseline	47.0	61.2	26.8	44.0
CC	28.2	39.6	11.6	21.0
ET	57.7	43.3	42.7	21.0
ET_{def}	46.6		20.0	
TDM	42.1		18.4	

Forecast results for the $CCFS_{RAD}$ are illustrated in Figure 21. Forecasted yields for zone 1 compared well with, and were slightly higher than actual yields. Forcing simulations with RS data did not improve forecast accuracy except, possibly forcing December forecasts with CC data. Increases in forecasted yields are observed when simulations are forced with ET. This is ascribed to the fact the RS ET data is lower than CCFS ET calculations, causing less extraction of water from the soil and more optimal soil water status levels. Forecasted yield also increased when simulations were forced with RS TDM data. This is ascribed to the fact that RD TDM data was higher than CCFS TDM calculations, causing more biomass to be partitioned to stalks.

Baseline $CCFS_{RAD}$ forecasted yields for zone 8 were much higher than actual yields, because the model does not account for suboptimal irrigation practices and agronomic management. Forcing the model with RS ET and TDM data reduced forecasted yields and improved the accuracy of April and December forecasts, while forcing with RS ET_{def} data improved the December forecast. Increases in forecasted yields and a reduction of accuracy were observed when simulations are forced with RS ET, due to reasons explained above.

Results for the $CCFS_{ET}$ model are shown in Figure 22. Forcing simulation with RS CC and ET data improved the April forecast for zone 8 and the December forecast for both zones. The small effect for zone 1 April forecast is because relatively little remote sensing data was available for replacement (November 2011 to March 2012).



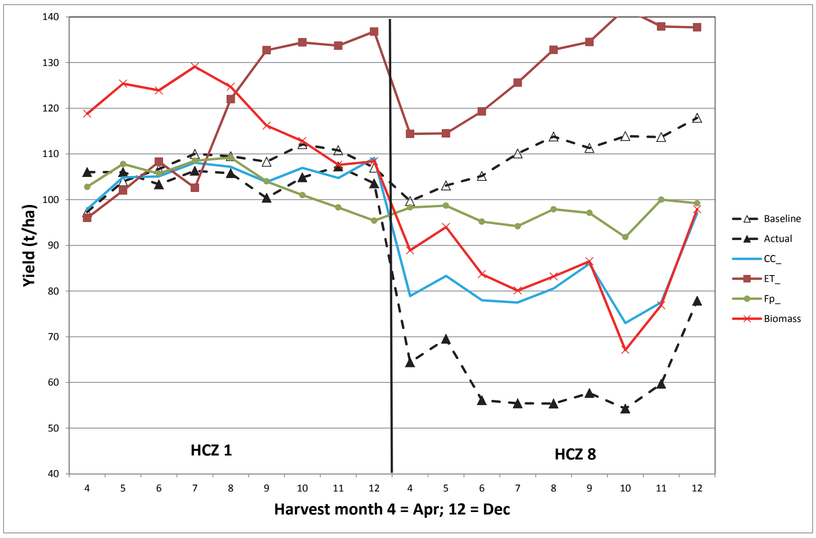
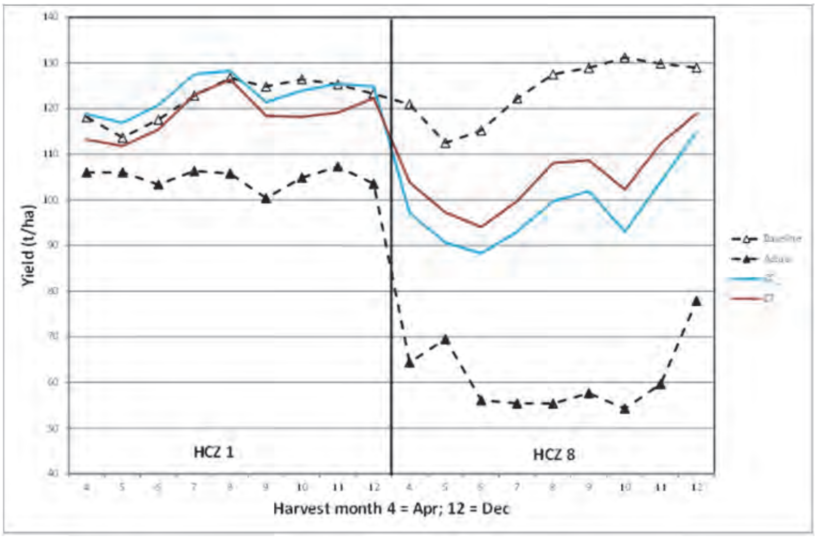


Figure 21. Cane yield forecasts from the $CCFS_{RAD}$ model forced with SEBAL estimates of canopy cover (CC), or evapotranspiration (ET), or without any SEBAL forcing (baseline), compared to actual yields for each harvest month for homogeneous climate zones (HCZ) 1 and 8, made in April (top) and December (bottom).



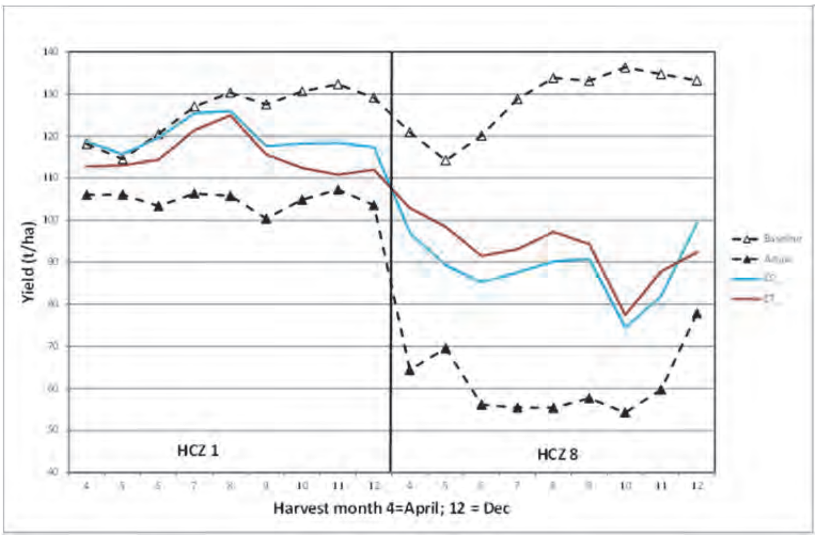


Figure 22. Cane yield forecasts from the $CCFS_{ET}$ model forced with SEBAL estimates of canopy cover (CC), or evapotranspiration (ET), or without any SEBAL forcing (baseline), compared to actual yields for each harvest month for homogeneous climate zone 1 and 8 made in April (top) and December (bottom).

Forecasted yield were up-scaled to mill level production by multiplying average yields for each zone and harvest month with the area harvested in the given zone in the given month and summing over zones and months. Only fields larger than 3 ha and harvested after April were considered. It should be noted that the inherent model bias were not removed and forecasts may therefore appear quite inaccurate. In operational forecasting, yields will be adjusted to remove the bias based on historical actual yield data. The criterion for success here is a reduction in the difference between the production forecast and the actual production.

The results in Table 16 show that the $CCFS_{RAD}$ production forecast error was reduced from 14.5 to 9.5 % in April and from 13.5 to 5.0 % in December when simulations were forced with CC data. Using SEBAL ET and TDM data as input did not improve the $CCFS_{RAD}$ forecasts. $CCFS_{ET}$ production forecast error were reduced from 28 to 23 and 21 % in April, and from 32 to 19 and 17 % when simulations were forced with CC and ET data, respectively.

The results suggest that remotely sensed CC and ET data can enhance model based sugarcane crop forecasting.

Table 14. CaneSim® forecasts of Komati mill cane production (tons) with and without SEBAL forced canopy cover (CC) and evapotranspiration (ET) data, compared to Mill Group Board (MGB) estimates and the actual production as obtained from the TSB database. Values in brackets are the percentage difference between the forecasts and the actual production value.

Forecast type	April 2012 forecast	December 2012 forecast	Actual production (March 2013)
MGB estimate[36]	2 179 316	2 198 352	1 957 775
MGB estimate (large fields)[37]	1 7937 195	1 809 463	1 611 444
$CCFS_{RAD}$ baseline	1 903 302 (14.5)	1 885 474 (13.5)	
$CCFS_{RAD}$ with SEBAL CC	1 819 336 (9.5)	1 745 162 (5.0)	
$CCFS_{RAD}$ with SEBAL TDM	2 077 472 (25.0)	1 971 628 (18.7)	
$CCFS_{ET}$ baseline	2 134 474 (28.5)	2 195 051 (32.1)	
$CCFS_{ET}$ with SEBAL CC	2 048 772 (23.3)	1 983 454 (19.3)	
$CCFS_{ET}$ with SEBAL ET	2 017 358 (21.4)	1 951 895 (17.5)	
TSB data base[38]			1 729 242
TSB data base (large fields)			1 661 657

[36] From an area harvested of 21 368ha (Singels *et al.*, 2014)
[37] From an area harvested of 17 588ha (TSB, 2013)
[38] From an area harvested of 18 559ha (TSB, 2013)

3.6 SEASONAL ESTIMATES OF SUGARCANE ET, ET_{DEF}, BIOMASS PRODUCTION AND WATER USE EFFICIENCY

The seasonal statistics for sugarcane is summarised in Table 15. The statistics (for the 2011/12 season) is based on data from an area of approximately 60 000 ha. Note: Data from all sugarcane fields in the MpCGA shape file was used. Since details of activities on each field were not available, it is possible that data from some fields that have been ploughed out, been converted into other crops or are lying fallow, are included in the statistics.

Table 15. Seasonal statistics of evapotranspiration (ET), Evapotranspiration deficit (ET_{def}), biomass (BIO) and biomass water use efficiency (WUE_{BIO}) estimated for sugarcane for the 2011/12 season

	SEBAL ET [mm/season]	SEBAL ET_{def} [mm/season]	SEBAL BIO [t/ha/season]	SEBAL WUE_{BIO} [kg/m3]
Mean	1092	244	47	4.1
Stdev	252	140	19	1

3.6.1 *Actual evapotranspiration (ET)*

The seasonal analysis for sugarcane covered the growing season from 17 November 2011 to 5 December 2012, a period of 385 days. Figure 33 shows the annual evapotranspiration spatially across the study area. Figure 24 shows the histogram of evapotranspiration for pixels with sugarcane. The accumulated ET ranged between 1000 to 1600 mm/season for the sugarcane fields located in the north-eastern and center regions of the study site. These regions correspond to areas with good irrigation infrastructure and with high production fields. In the southern region accumulated ET values ranged between 600 to 1000 mm/season. The lower ET in these areas (typically from small growers) is the result of poorly maintained irrigation infrastructure, under designed irrigation system, required irrigation system sharing and poor management conditions (Cronje, 2014). Actual ET values of 1000 to 1300 mm/season are frequent (Figure 24) and typically correspond with areas owned by large commercial growers.

Average ET values from this study compare well with those estimated for this area by Hellegers *et al*. (2009) (1050 mm) and Bezuidenhout *et al*. (2006) (1016 mm).

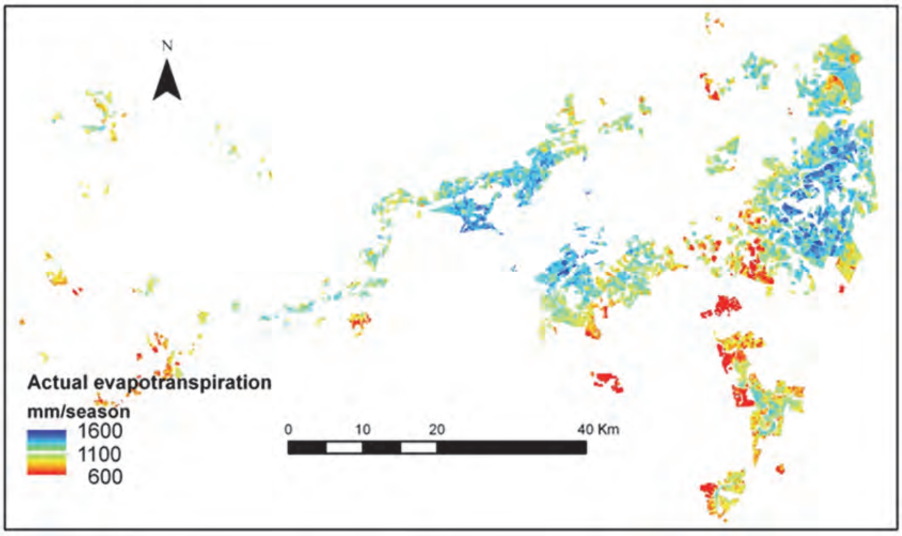


Figure 23. Actual evapotranspiration for sugarcane fields for the growing season from 17 November 2011 to 5 December 2012

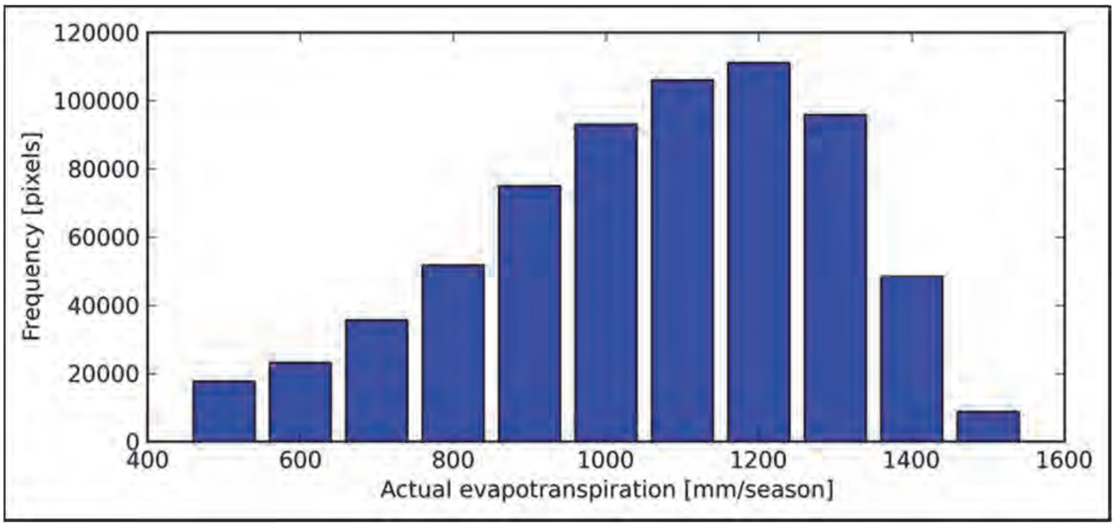


Figure 24. Histogram of actual evapotranspiration for pixels on sugarcane fields for the growing season from 17 November 2011 to 5 December 2012

3.6.2 Evapotranspiration deficit (ET_{def})

Figure 25 shows the spatial distribution of the accumulated ET_{def} and Figure 26 presents the ET_{def} histogram for the sugarcane pixels. Accumulated ET_{def} between 100 and 200 mm was frequent (Figure 26). Above this range, the distribution of pixels reduced with increments of evapotranspiration deficit values. Interesting to note also is that the areas delivering to the Malelane mill (Figure 3) typically had lower ET_{def} than the areas delivering to the Komatipoort mill. The Malelane area is climatically slightly cooler, wetter and also receives a higher irrigation allocation than the Komatipoort area. The typically higher ET_{def} in the Komatipoort area relates to lower water allocation, higher atmospheric demand and reference sugarcane crop evapotranspiration, suggesting water shortages in this area.

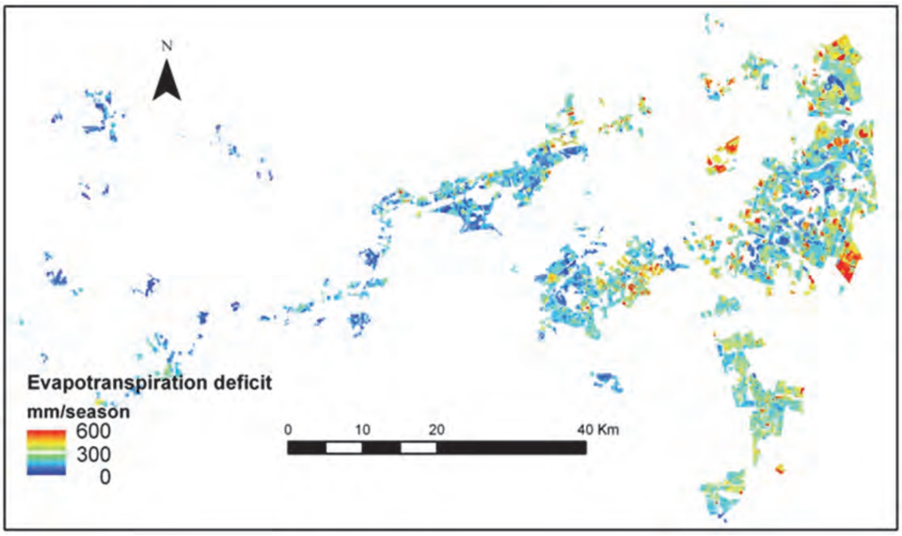


Figure 25. Evapotranspiration deficit for sugarcane fields for the growing season from November 2011 to 5 December 2012

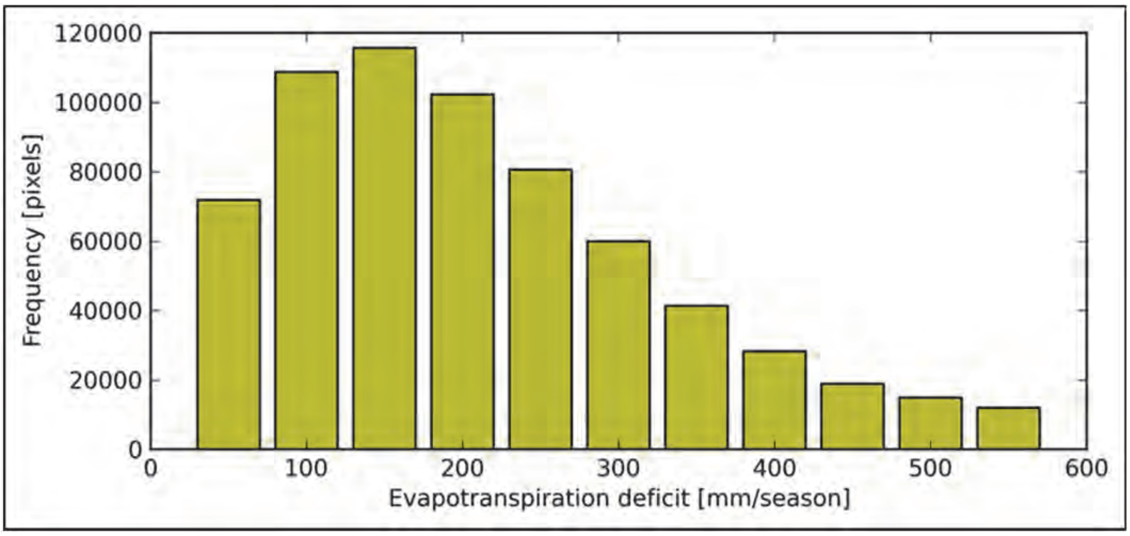


Figure 26. Histogram of evapotranspiration deficit for pixels on sugarcane fields for the growing season from November 2011 to 5 December 2012

3.6.3 Actual biomass production

The actual biomass production corresponds to the accumulated total (dry above and below ground) biomass production during the growing season. The biomass production was very heterogeneous over the study area and Figure 27 shows the spatial distribution of the accumulated dry biomass production and Figure 28 the biomass production histogram for pixels with sugarcane. Fields with high biomass production, with values larger than 40 t/ha/season corresponded with large commercial fields located in the central and north-eastern regions. Fields with lower actual biomass production, with values lower than 40 t/ha/season were concentrated in the western and southern regions where small growers are typically localized. The difference in actual biomass production by these growers can possibly be explained by less optimal fertilizer and irrigation applications. This is reflected in the differences of attained biomass production between large commercial farmers and small growers.

Hellegers *et al*. (2009) found average biomass values of 55 to 59 t/ha for the Inkomati basin which corresponds well with the values found in this study.

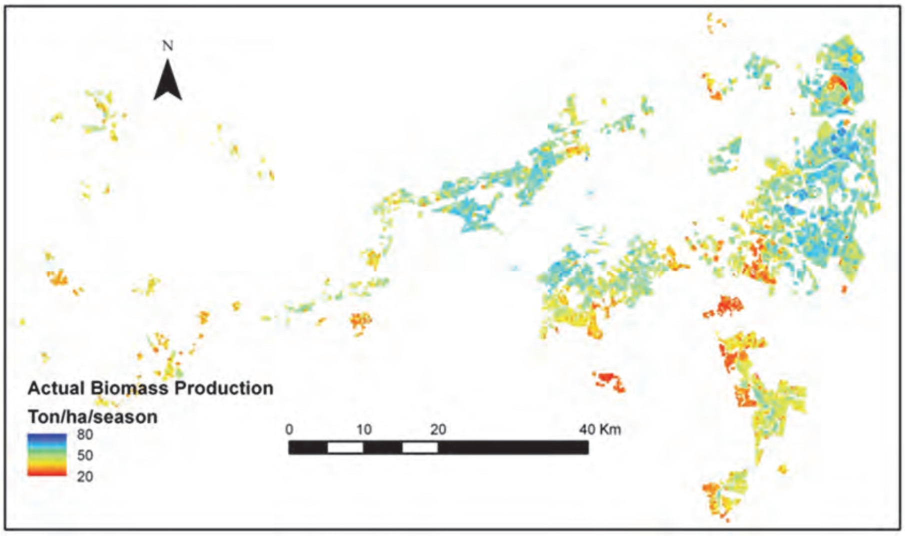


Figure 27. Total biomass production for sugarcane fields for the growing season from November 2011 to 5 December 2012

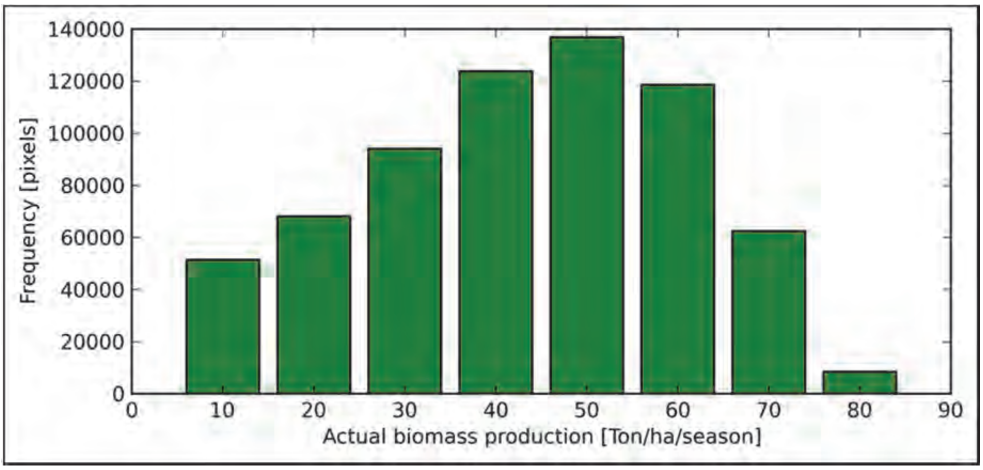


Figure 28. Histogram of Total biomass for pixels on sugarcane fields for the growing season from November 2011 to 5 December 2012

3.6.4 Biomass water use efficiency (WUE_{bio})

Figure 29 shows the spatial distribution of biomass water use efficiency across the sugarcane study area and Figure 30 the histogram of WUE_{BIO} for pixels with sugarcane. The values present the average for a growing period[39]. The WUE_{BIO} is fairly homogenous over the area with a large proportion of the fields with values between 3 and 5 kg/m^3. The lower WUE_{BIO} with values lower than 3 kg/m^3 corresponded typically with the small grower areas.

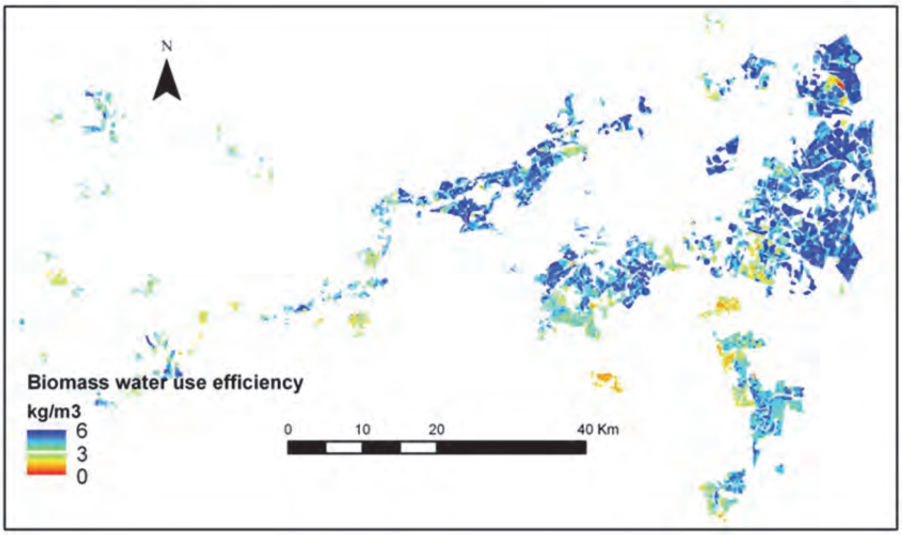


Figure 29. Average seasonal biomass water use efficiency for sugarcane fields for the growing season from November 2011 to 5 December 2012

[39] The growing period was defined here by the available data 1 November 2011 to 5 December 2012 and will included data from periods of two consecutive sugarcane crops grown.

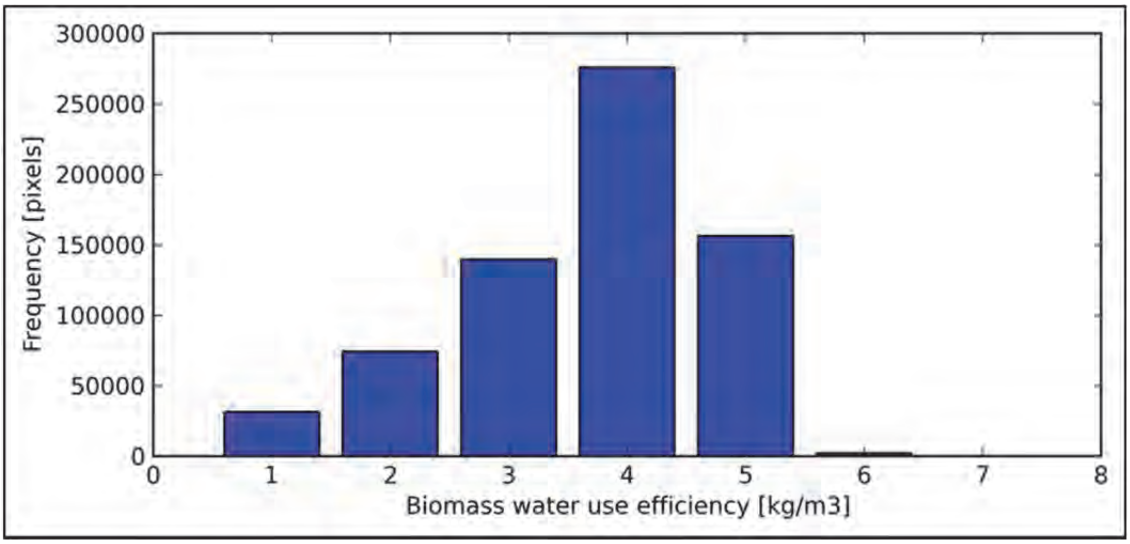


Figure 30. Histogram of biomass water use efficiency for pixels on sugarcane fields from November 2011 to 5 December 2012

The WUE_{BIO} time series for each field during the study period was also plotted. In Figure 31 the WUE_{BIO} for different field groupings – e.g. according to irrigation system (centre pivot, drag line, drip or sub-surface drip) and harvest dates (summer and winter) are shown and this reveals interesting trends over time. For example:

- WUE_{BIO} estimates for the two centre pivots differed. WUE_{BIO} for Field 72 was consistently high, whereas that for field G7 varied over time. The periods of low WUE_{BIO} for field G7 was due to irrigation system limitations which led to water stress.
- WUE_{BIO} from the two fields with draglines was generally lower than for all other systems in 2011/12, but field 17 specifically performed well during the 2012/13 season with WUE_{BIO} similar to the other systems. The low WUE_{BIO} for field 17 from February 2013 onwards was because this field was ploughed out and the WUE_{BIO} hence reflects a fallow field.
- For both drip and sub-surface drip, the WUE_{BIO} between the fields showed some variation but probably more during the period of maturation and drying off. During the peak summer season WUE_{BIO} estimates were similar in the respective fields.
- Also interesting to note is that the WUE_{BIO} of the two fields harvested in summer were nearly identical, despite different irrigation systems (centre pivot and sub-surface drip), whereas the WUE_{BIO} for fields harvested between May and August varied greatly. WUE_{BIO} from fields harvested in summer never showed the very low WUE_{BIO} visible for the fields harvested in winter, possibly due to the fast regrowth in these fields with summer plantings.
- Interesting that over the season, the highest WUE_{BIO} for the 2012/13 season was for 8C (8.1 kg/m^3).

WUE_{BIO} for sugarcane (from remote sensing data) has only been reported by Hellegers *et al*. (2009) to range between 0.5 and 4 kg/m^3. WUE is normally quoted in units of fresh cane yield per unit of ET, which can be converted to WUE_{BIO} assuming a stalk fraction of 57% and stalk dry matter content of 25%. Values reported in the literature for well managed crop range from 4.2 to7.5 kg/m^3 (Olivier and Singels, 2003, Kingston, 1994; Thompson, 1976). WUE_{BIO} values below 4.0 kg/m^3 can be considered low and indicate inefficient conversion of ET to biomass possibly due to agronomic limitations such as weed, pests and disease pressure, nutrient deficiencies, poor crop stand or high levels of evaporation from the soil. These can then be targeted for corrective action.

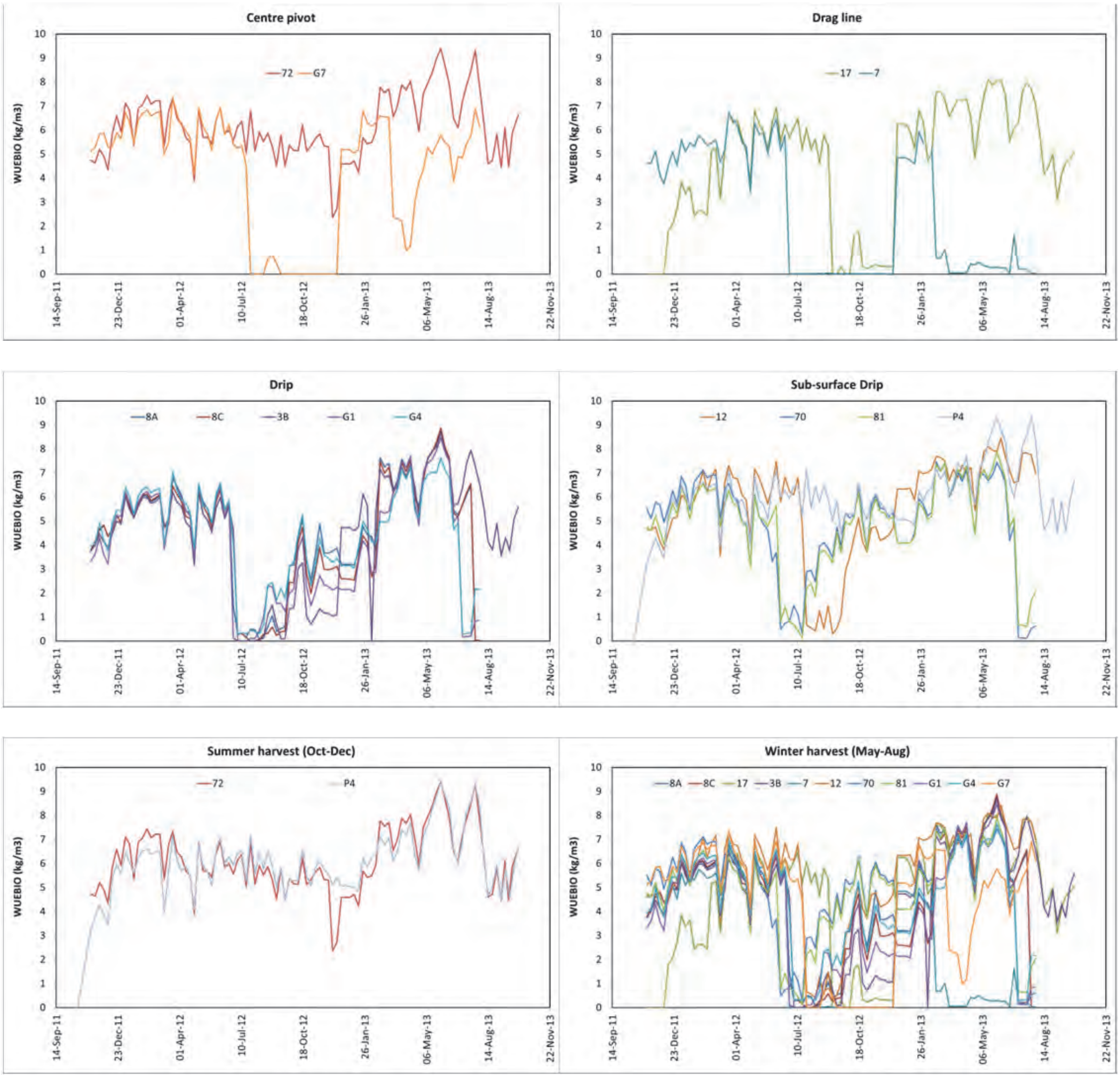


Figure 31. Time series of Biomass water use efficiency for the period 1 November 2011to 20 November 2013 for all sugarcane fields studied. Data is group first according to irrigation system and then according to the month of harvest.

3.7 WATER USE EFFICIENCY

The water use efficiency defined as stalk dry mass harvested divided by seasonal total ET for 11 of the sugarcane fields harvested in 2013 ranged between 1.94 and 3.4 kg/m^3 (Figure 32,Table 16). The values represent the average over the 2012/13 season. Typically the estimates based on the observations and simulations were very similar, with the exception of two fields (G1, G4).

Values from the literature for well managed crops range (assuming a stalk dry matter content of 25 %) from 2.4 to 4.4 kg/m3. Fields 8C and 3B had WUE_{SDM} values below 2.4, suggesting the presence of yield limiting factors. This corresponds to the MyCaneSim® review of crop performance in Appendix III. Hellegers *et al*. (2009) found crop WUE on commercial sugarcane farms to be 1.25±0.21 kg/m^3 and on emerging farms 1.14±0.17 kg/m^3.

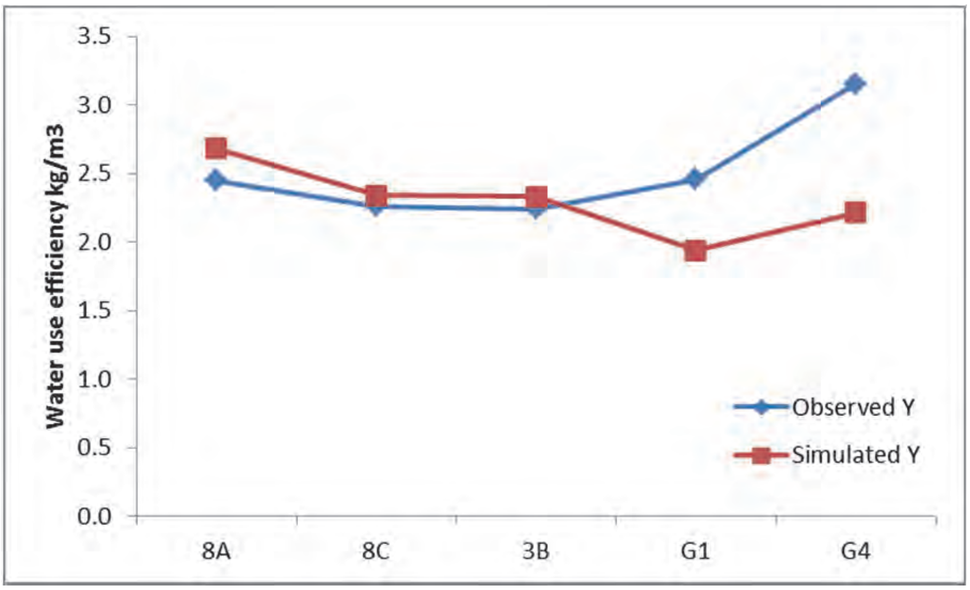


Figure 32. Water use efficiency of 11 of the sugarcane fields studied. The WUE was estimated from SEBAL estimates of ET and Observed and simulated harvestable yields.

Table 16. Statistics related to the water use efficiency estimated for 11 of the sugarcane fields studied. The WUE was estimated from SEBAL estimates of ET and the observed and simulated yields for these fields.

Water use efficiency	Obs Y/SEBAL ET kg/m3	TT Sim Y/SEBAL ET kg/m3
Ave	2.74	2.70
StDev	0.34	0.46

CHAPTER 4: ESTIMATING WATER USE EFFICIENCY OF IRRIGATED MAIZE

4.1 STUDY AREA 2: IRRIGATED MAIZE

The maize study area of this project was located in the Northern Cape Province of South Africa. Although this Province only has an estimated 51 500 ha under irrigated maize (1.85 % of the country total area), it produced an estimated 651 650 tons or 5.7% of South Arica's maize in 2013, hence it is an important production area. GWK is the major grain cooperative in the area and was the commercial partner in this component of the project.

The study area covered an area of 60 km x 60 km around the town of Douglas. A range of summer and winter grains and other crops are produced in this area. Maize and wheat are the dominant summer and winter grains (Figure 33) used in a dual cropping systems in this area.

Douglas is situated at an average altitude of 1029 m and has a semi-arid climate. Douglas receives an average annual rainfall of approximately 339 mm (Haarhoff, 2014) and average mid-day temperatures of 18.4 °C. Douglas is located near the confluence of the Orange and Vaal Rivers. Apart from the areas under irrigation, land is sparsely cultivated and covered with closed to open grassland. The soil type varies over this area but can be described as arenosols with sandy/loamy textures. Generally the soils have a high magnesium content, with yellow sands occurring next to the Orange River, red sands next to the Vaal and Riet Rivers and some areas having heavy clayey soils.

Centre pivot irrigation systems are used almost exclusively to irrigate crops in this study area. The total area under irrigation is about 21 750 ha and falls under the jurisdiction of the Orange/Riet and Orange/Vaal Water Users Associations. Irrigation water is sourced from the Vaal, Riet and Orange Rivers. Irrigation takes place in a 250 km radius around Douglas. The water allocation for irrigation is typically in the order of 1000-1100 mm/yr.

4.1.1 Selected fields

Within the Douglas study area, numerous crops are cultivated. A total of fourteen fields were selected to be monitored in detail representing a selection of these crops: seven fields planted with maize and the others planted to lucerne, mixed pastures, sunflower and groundnuts. An additional three potato fields were added towards the end of the monitoring period. For this report, only data from the maize fields (Figure 34)[40] was selected since it is the most important summer grain crop. The evaluation of the data from the maize fields should provide a good indication of the applicability of the technology in this region, also to other crops and for other areas under maize production. Details of each of the maize fields are provided in Table 17. The preceding crop for all the maize fields was wheat.

[40] Note: Two MSc students will report on the results for other crops (M. Dlamini and D. Taverna-Turisan) as well as another WRC project on lucerne and pastures (K5/2173/4, Truter *et al*., 2014).

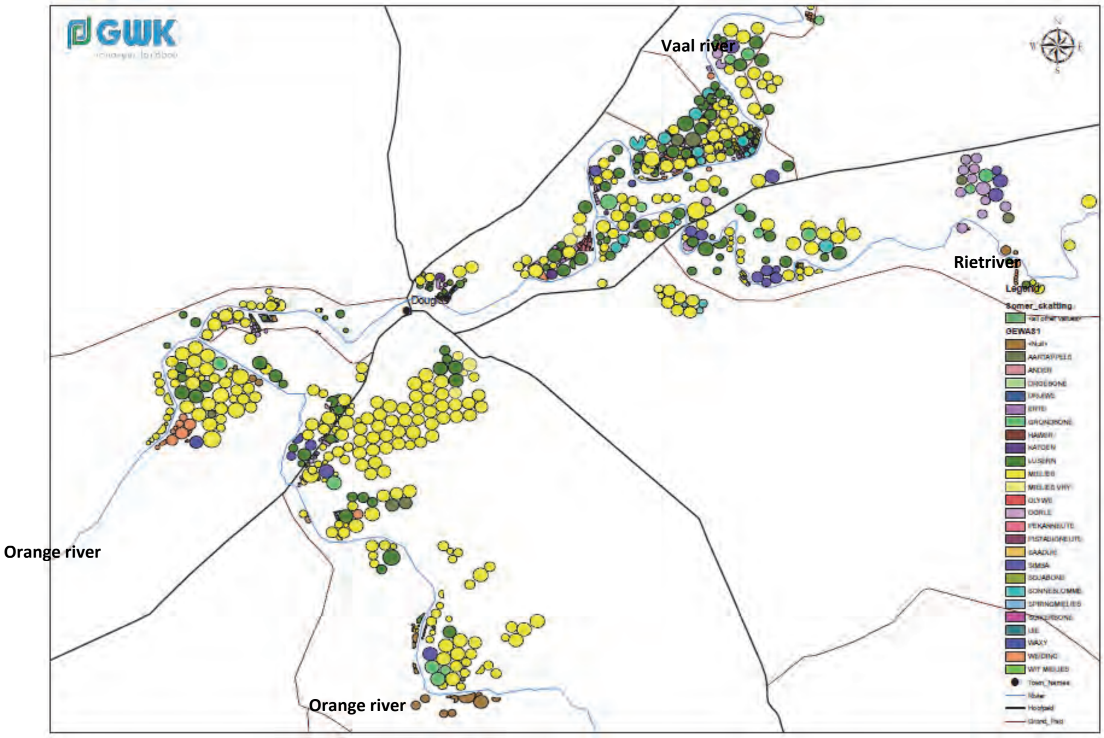


Figure 33. The extent of centre pivots in study area 2, mainly cultivated with maize around the town of Douglas, but including other crops. Yellow pivots represent maize.

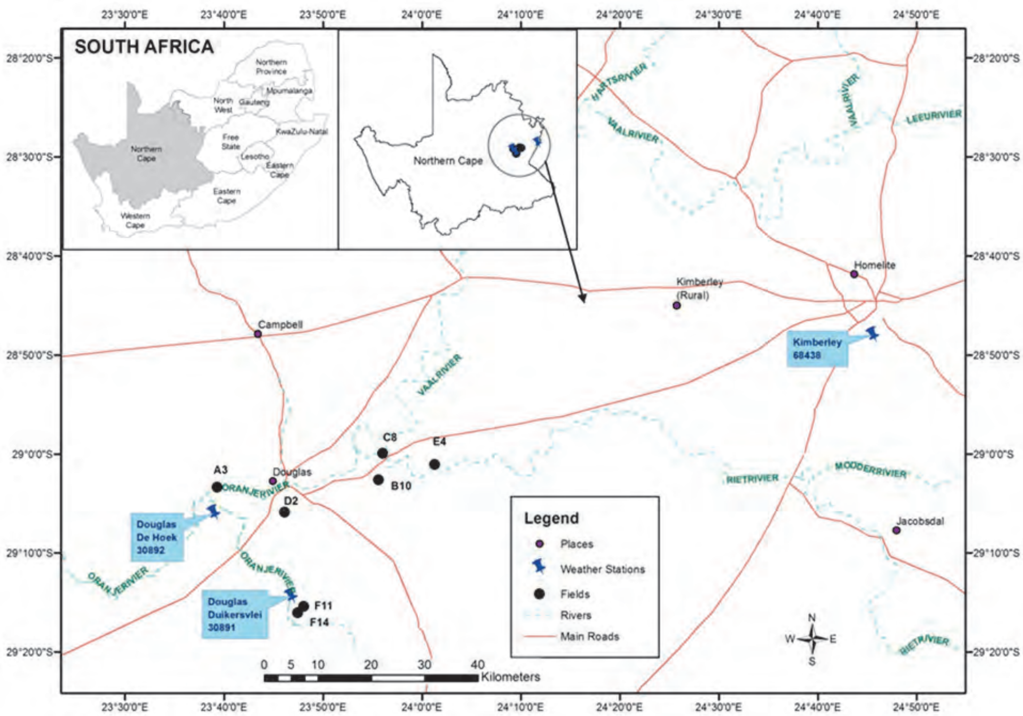


Figure 34. The location of the selected maize fields studied extending along the three important river systems (Vaal, Orange and Riet rivers)

Table 17. Details on each of the maize fields studied in this project

Field	Coordinates	Crop (cultivar)	Planting date	Sampling dates	Harvest date	Soil depth (m)	Soil texture	Soil Bulk Density (kg/m^3)
A3	29° 03.345′ S 23° 39.317′ E	Maize (Short grower)	22-12-2012	09-01-2013 09-02-2013 22-02-2013 14-03-2013 19-03-2013 30-04-2013	30-05-2013	0.6[41]	Loam	1.59
B10	29° 02.625′ S 23° 55.608′ E	Maize (Short grower)	26-11-2012	10-12-2012 09-01-2013 04-02-2013 22-02-2013 04-03-2013 20-03-2013 30-04-2013	30-05-2013	1.2	Loamy sand	1.65
C8	28° 59.910′ S 23° 56.025′ E	Maize (Short grower)	13-12-2012	09-01-2013 06-02-2013 22-02-2013 04-03-2013 20-03-2013 30-04-2013	30-05-2013	0.9[42]	Sandy loam	1.47
D2	29° 05.859′ S 23° 46.129′ E	Maize (Short grower)	12-12-2012	09-01-2013 09-02-2013 21-02-2013 14-03-2013 22-03-2013 30-04-2013	30-05-2013	1.2	Loamy sand	1.45
E4	29° 01.05′ S 24° 01.33′ E	Maize (Short grower)	05-12-2012	09-01-2013 05-02-2013 20-02-2013 07-03-2013 18-03-2013 30-04-2013	30-05-2013	1.2	Sand	1.62
F11	29° 15.391′ S 23° 48.065′ E	Maize (Short grower)	14-12-2012	10-01-2013 07-02-2013 19-02-2013 14-03-2013 21-03-2013 01-05-2013	30-05-2013	1.2	Loamy sand	1.49
F14	29° 16.061′ S 23° 47.454′ E	Maize (Short grower)	07-12-2012	10-01-2013 07-02-2013 19-02-2013 14-03-2013 21-03-2013 01-05-2013	30-05-2013	1.2	Loamy sand	1.48

4.1.2 Study period

The selected fields were studied from 1 October 2012 to 31 May 2013, covering the end of the wheat growing season and the entire maize growing. Most of the maize modelling and sampling was done between November 2012 and May 2013 (Table 17).

[41] Heavily compacted layer at 0.6 m
[42] Gravel bed at 0.9 m

4.2 FIELD MEASUREMENTS OF SOIL AND WATER RELATED PARAMETERS

4.2.1 Soil analyses

Soil samples were taken for particle size analysis according to the hydrometer method and the bulk density was determined by oven drying soil cores of known volume, then dividing the oven dry mass by the volume of the soil (Table 17). Samples were taken in close proximity to the Neutron Water Meter (NWM) sampling point, using a soil auger to a depth of 1.2 m, unless there was a restricting layer at a shallower depth.

4.2.2 Soil water balance

Soil water content (SWC) was measured weekly to a depth of 1.2 m at a single point in each field using a neutron water meter (NWM). Precipitation data was obtained from the nearest weather station to the specific field and irrigation was recorded using manual rain gauges installed at each monitoring site. Evapotranspiration was estimated as the residual of the soil water balance equation (Eq. 21):

$$ET = P + I - R - DP + CR \pm \Delta S \quad (21)$$

where ET is the Evapotranspiration , P is Precipitation, I is Irrigation, R is Runoff, DP is Deep percolation, CR is Capillary rise and ΔS the change in SWC.

In this case, deep percolation, runoff and capillary rise were all assumed to be negligible and hence set to zero. Unfortunately irrigation data from the rain gauges were generally judged to be unreliable after a certain point in time, as the maize canopy grew above the gauges. Irrigation measurements were also not made in certain instances due to destruction of gauges by farm implements.

When irrigation data was not available, I and R were estimated by 'back-calculating' a cumulative weekly value (I+R) using real time reference evapotranspiration (ET_o), a crop factor (k_c) obtained from GWK and the SWC data. This daily ET_o was multiplied by the relevant (crop specific) k_c to give an estimation of weekly crop evapotranspiration (ET) throughout the growing season. The change in SWC (or ΔS) is determined by subtracting each week's SWC reading by the SWC of the previous week. The input of water (I+R) into the soil profile can then be estimated by adding/subtracting ΔS to/from ET (Eq. 22).

$$(I + R)_{weekly} = (ET)_{weekly} \pm (\Delta S)_{weekly} \quad (22)$$

Irrigation was then determined by subtracting R (obtained from weather station) form (I+R). The derived (I+R) values were compared to measured rain gauge data from before the maize canopy grew above the gauges. A strong correlation was found (R^2= 0.91) for the comparison between the first rain gauge measurement and the derived (I+R) value of each field. An R^2 of 0.86 was found when comparing the first two rain gauge measurements per field to the derived (I+R) values.

4.2.3 Evapotranspiration measurements

For comparison with the spatial energy balance and evapotranspiration data sets estimated with the SEBAL model, a one-sensor eddy covariance (EC) system with a CSAT-3 sonic anemometer was installed in a maize field in December 2012, at the time of planting (Figure 35) and only removed shortly before the maize was harvested[43].

The eddy covariance method estimates the sensible heat flux density and combining this with measured net radiation and estimated soil heat flux, the latent energy and ET is estimated as the residual of the energy balance equation (Eq. 3) (Savage *et al*., 2010). The eddy covariance system has been widely applied in South Africa (Savage *et al*., 2010; Clulow *et al*., 2012; Jarmain *et al*., 2009a) and elsewhere.

Figure 35. One sensor eddy covariance system with CSAT-3 sonic anemometer installed close to the centre of a pivot planted with maize. The EC system is here shown at full canopy cover as the pivot moves over it, and prior to harvest.

4.3 FIELD MEASUREMENTS OF CROP GROWTH

4.3.1 Dry matter accumulation

Crop dry matter measurements were taken in close proximity to the NWM access tubes at two week intervals by destructively harvesting plant samples from an area of 1.56 m^2. Samples were partitioned into leaves, stems and cobs and oven dried at 60°C for three days to 0 % moisture (samples were dried until a constant weight was obtained). Three random replications were sampled per field on the dates indicated in Table 17.

4.3.2 Canopy cover

Leaf area index (LAI) was measured non-destructively with a ceptometer (AccuPAR LP-80, Decagon, Pullman, Washington) and destructively using a leaf area meter. Fractional interception (FI) of photosynthetically active radiation (PAR) was determined by comparing above and below canopy PAR, measured with a ceptometer (Eq. 23). Canopy cover (CC) was calculated from FI as represented in Eq. 24.

$$FI = 1 - (PAR_{below}/PAR_{above}) \quad (23)$$

$$CC = FI * 100 \quad (24)$$

[43] A second one-sensor eddy covariance system was installed in the study area in January 2013 over a field of lucerne, but the data will not be shown or discussed here. See K5/2173/4 (Truter *et al*., 2014).

4.3.3 Leaf nitrogen levels

During each measurement campaign, the youngest fully developed leaf (a composite sample from several plants) was submitted to the SGS (Société Générale de Surveillance, Agricultural Laboratory, Cape Town) for nitrogen (N) concentration estimation.

The SPADOMETER (SPAD-502Plus, Konica Minolta) chlorophyll meter was used to measure leaf 'greenness' and investigate correlations between leaf N concentration and measurements from satellite images. The SPADOMETER typically takes readings in the range 605 and 940 nm.

4.3.4 Stomatal conductance

Stomatal conductance was measured with a leaf porometer (SC-1 Leaf porometer, Decagon, Pullman, Washington) to assess how actively the plants were transpiring. Abaxial and Adaxial measurements were taken at various plant heights. Measurements were done to correlate low leaf transpiration with SEBAL estimated incidences where water stress was evident.

4.3.5 Cob dry matter and grain yield

Cob dry matter (0 % moisture) was measured throughout the season and a final measurement was made at the end of April 2013. The cob dry matter included both the cob and the grain.

The final grain yield was also obtained for six of the seven fields monitored from the precision combine harvesters. These precision grain yield map data was corrected to a moisture content of 0 %.

4.4 MODELLING WATER USE EFFICIENCY WITH THE SOIL WATER BALANCE MODEL

The Soil Water Balance (SWB) model is a mechanistic, real time, generic, crop growth, soil water balance and irrigation scheduling model (Annandale *et al*., 1999; Singels *et al*., 2010). SWB was developed based on the NEWSWB model from Campbell and Diaz (1988). There are two versions of the model: (a) a simple irrigation scheduling version (SWB-Pro) and (b) a research version (SWB-Sci) (Annandale *et al*., 1999; Singels *et al*., 2010; Annandale *et al*., 2011).

SWB estimates crop growth and water balance fluxes using weather, crop and soil units. SWB estimates reference daily evapotranspiration (ET_o) using the Penman-Monteith equation according to FAO 56 recommendations (Allen *et al*. 1998). Dry matter production is simulated mechanistically by calculating a daily dry matter increment, which is limited by either radiation or water availability. Phenological development, growth and yield of a crop from planting to maturity are mechanistically estimated based on soil water status and environmental conditions. Yield here refers to the total of grain and cob mass. Water-limited growth is estimated using parameters that directly limit biomass accumulation, including a crop water stress index (Annandale *et al*., 2000). The big advantage of this approach over crop factor based approaches to water balance modelling, is the feedback between soil water availability and the growth and development of the crop canopy. The use of thermal time in SWB avoids the need to use different crop factors to express crop development for different planting dates and regions (Annandale *et al*., 1999). Either a cascading (also called 'tipping bucket') or finite difference approach can be used to simulate water movement between layers within the soil profile.

The main processes of the nitrogen (N) sub-model are described in detail by Van der Laan (2009). These processes include estimating crop N demand, actual crop N uptake, N transformations and various loss pathways. SWB-Sci follows a similar approach to that of CropSyst, by grouping C3 or C4 crops in estimating crop N demand and potential crop N uptake (Godwin and Jones, 1991; Stöckle *et al*., 2003).

SWB simulations for each field were set up and parameterized based on information presented in Table 17. Crop parameters were calibrated using data from field F14 and are presented in Figure 36. Each field was further calibrated against the observed yield.

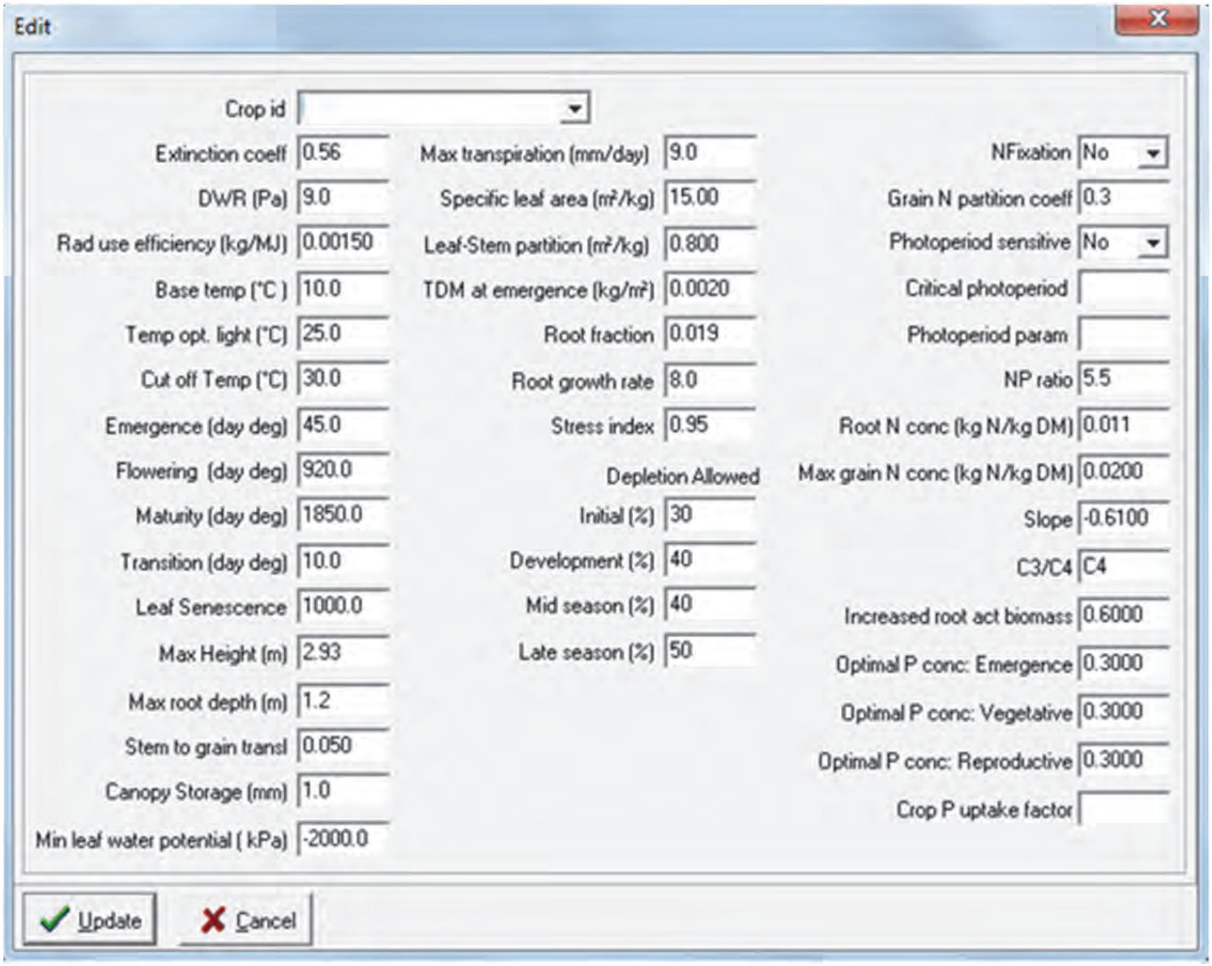


Figure 36. SWB crop parameters used to simulate the short grower maize crop

4.5 CROP WATER REQUIREMENTS OF MAIZE WITH SAPWAT

The SAPWAT computer program is an irrigation planning and management tool and is a further development of CROPWAT (Smith, 1992). It is not a crop growth model and do not provide scheduling advise; rather it was developed to establish a decision-making procedure for the estimation of crop irrigation requirements by irrigation engineers, planners and agriculturalists (van Heerden *et al.*, 2008). The basic SAPWAT model has already been described in this report (See Section 2.4). The SAPWAT simulations were set up based on field specific information presented in Figure 37 and Figure 38, for short maize growers and using long term climatic data.

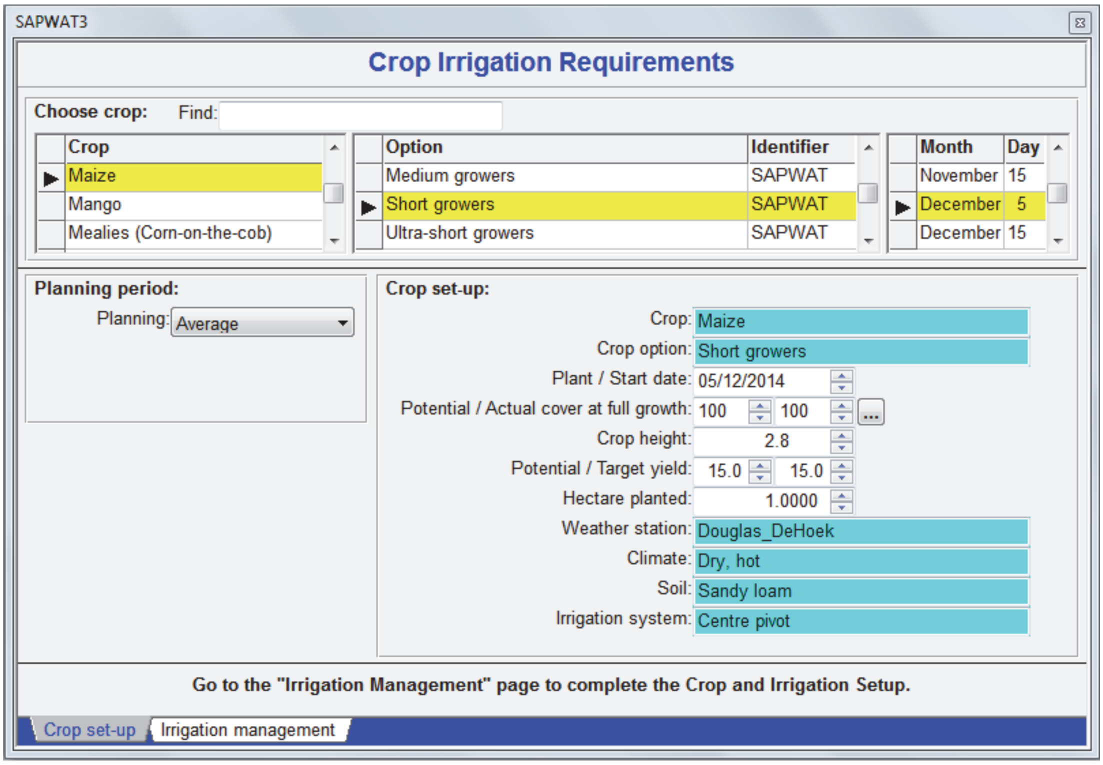


Figure 37. SAPWAT crop set up interface screen with parameters shown for a short grower maize crop

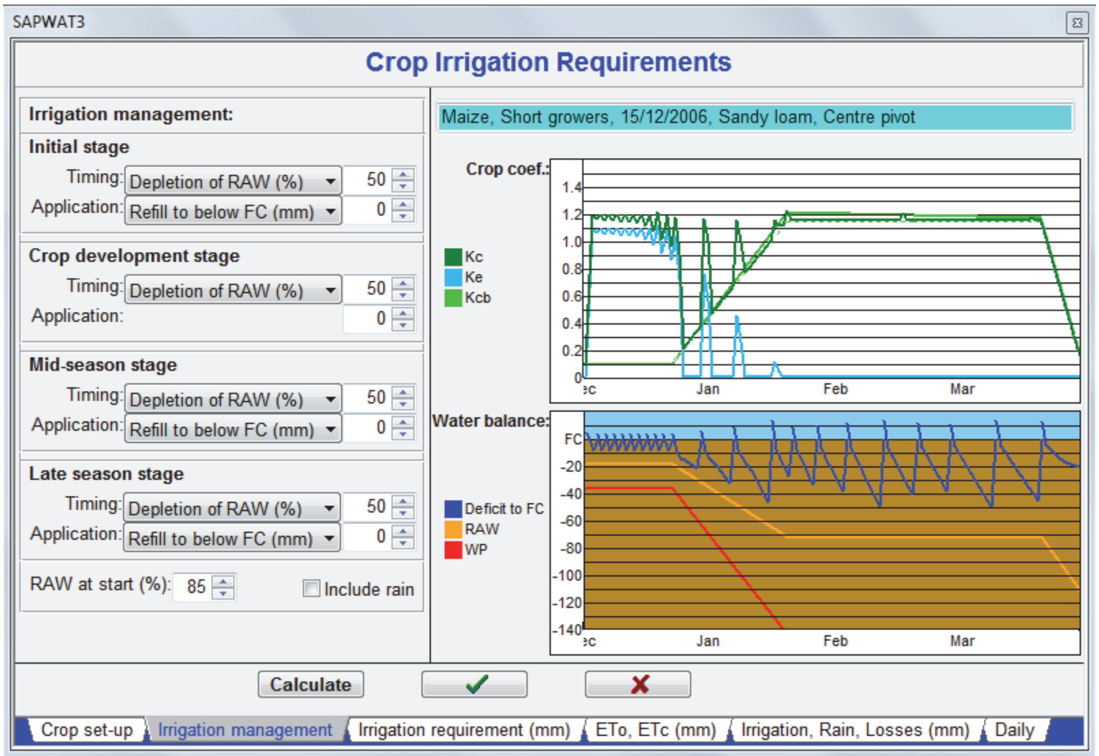


Figure 38. SAPWAT irrigation management interface screen

4.6 SEBAL SPATIAL MODELLING

The SEBAL model, described in Section 2.5.1, was used to estimate the water use efficiency of maize spatially. Similar procedures followed to estimate ET, potential ET, ET deficit and biomass production of sugarcane, were followed for maize. The approach followed to calibrate the biomass production for maize is described below, as well as the methods to estimate maize yield and nitrogen content in the maize plants.

4.6.1 Biomass production calibration and estimation of above ground dry matter production

The calibration of SEBAL biomass for maize followed a similar approach to that applied for sugarcane described (Section 2.5.1.4.1). First of all a C4 SEBAL (total) biomass was estimated where after the SEBAL C4 above dry matter was estimated.

The above ground dry biomass of maize was measured throughout the growing season and this was compared to the SEBAL C3 biomass data. Figure 39 presents the correlation between the SEBAL total C3 dry biomass (above plus below ground) and the measured above ground dry biomass (stem, leaves, cob). The slope of the regression line was 0.86, showing that the SEBAL estimates have to be adjusted. The slope of 0.86 was used to compensate for the above and below dry biomass calculations and a new maximum light use efficiency of 3.2 g/MJ was calculated for maize and applied to the data to estimate C4 SEBAL (total) biomass.

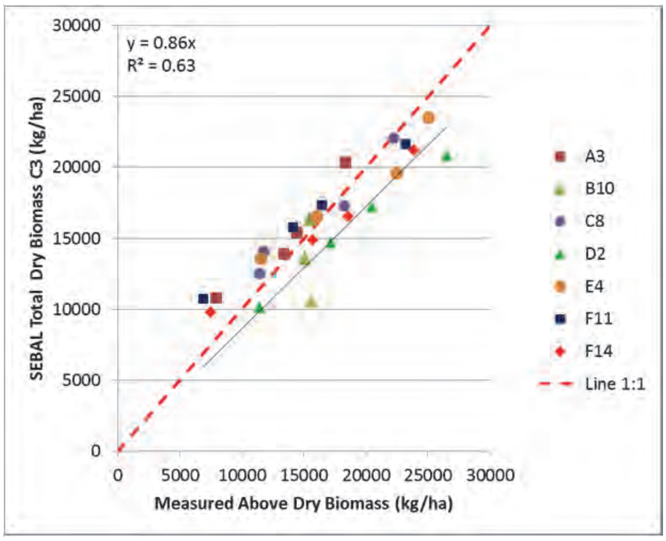


Figure 39. Correlation between SEBAL Total Dry Biomass C3 and Measured Above ground Dry Biomass for maize

Next SEBAL C4 ADM was estimated. First the SEBAL canopy cover data was plotted against the C3 biomass production to determine the point when vegetative growth has slowed down and no more or few leaves are produced (Figure 40). It is evident from Figure 40 that the vegetative growth slows down when a canopy cover of roughly 70 % is reached. From this point onwards (CC > 70 %) until harvest the below ground biomass or root partitioning was set to 10 %. Prior to this, the root partitioning was set to decrease linearly from 40 to 10 % with canopy cover. Thus, the proportion of biomass partitioned to the roots, will decrease linearly with increments of canopy cover (Figure 40). A similar approach in terms of root partitioning is currently applied in SWB.

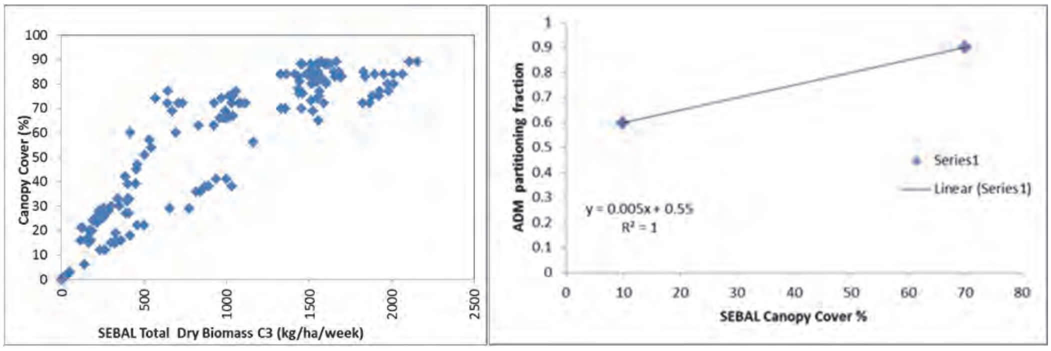


Figure 40. (left) Canopy cover from satellite data and SEBAL Total Dry Biomass C3 and (right) the linear regression used for ADM partitioning as a function of Canopy cover

Figure 41 shows the correlation between measured above ground biomass and the SEBAL C4 above ground matter estimates. The data correlation showed an R^2 of 0.93, with the SEBAL above ground dry biomass overestimating the values of dry biomass with 7%. This relationship can probably be improved by varying the below ground biomass partitioning using a non-linear relationship.

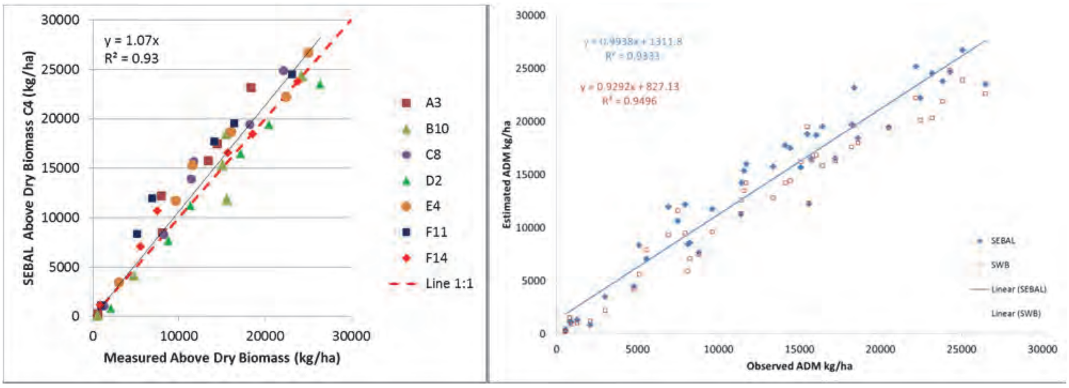


Figure 41. Correlation between SEBAL Above ground Dry Biomass C4 and Measured Above ground Dry Biomass for maize

4.6.2 SEBAL yield modelling and water use efficiency of maize

SEBAL does not produce estimates of grain yield, but only total biomass production from which above dry matter and yield can be estimated.

Grain yield is typically estimated in two ways: (a) using a Harvest index (HI)[44] (Eq. 25), representing the fraction of total C4 ADM that is partitioned into the grain (Eq. 26) or (b) accumulating the ADM from flowering and when vegetative growth has ceased (Eq. 27). The use of the Harvest Index to estimate yield (Eq. 26) is less favorable since it does not include a water stress factor required to explain yield variability over an area. However, identifying the date of flowering and cessation of vegetative growth from remote sensing data are also complex. Time series analysis of NDVI, albedo or canopy cover could possibly indicate the date of flowering and the end vegetative growth. In Douglas, flowering in maize occur around 75 to 80 days after planting.

[44] The harvest index is typically affected by moisture stress, but in this project it was calculated directly without trying to define the stress factor.

$HI = Yield_{GRAIN}/ADM_{total}$	*(25)*

$Yield_{GRAIN1} = HI.ADM_{total}$	*(26)*

$Yield_{GRAIN2} = \sum_{i=flowering}^{i=harvest} ADM$	*(27)*

Water use efficiency of maize was estimated from the crop grain yield data and the seasonal SEBAL ET estimates (Eq. 28). The grain yield data from the combine harvester and the accumulated SEBAL ADM approach (Eq. 27) were used. Since the SWB model only estimates total dry harvestable matter (cob plus grain), this data could not be used to estimate WUE.

$WUE_{GRAIN} = Yield_{GRAIN2}/ET_{SEBAL}$	*(28)*

4.6.3 Nitrogen modelling

Plants use chlorophyll for capturing light energy and using photosynthesis. There are different types of chlorophyll but chlorophyll-a and chlorophyll-b take an important part in the absorption of the light energy. The higher the chlorophyll content, the higher the biomass production. Chlorophyll-a and -b are usually absorbed at 0.65 µm and thus it can be assessed with field instruments measuring the absorption at this wavelength. These chlorophyll content meters are very effective on the field because leaf nitrogen and chlorophyll concentration are closely linked since the majority of leaf concentration is contained in chlorophyll molecules.

eLEAF has developed a chlorophyll index that takes into account the green, red and near infrared spectral bands in order to obtain an index that corresponds to high and low chlorophyll content The results of this index are transformed into chlorophyll content and then into nitrogen content of the upper layers of leaf. Based on the leaf area index this information is used to produce an estimate of the total nitrogen for the canopy (in kg/ha).

4.6.4 Data inputs

4.6.4.1 Spatial data

The spatial modelling for the maize production area was done for an area roughly covering 60 km x 60 km around the town of Douglas in the Northern Cape. A combination of DMC and VIIRS data was used here. DMC again captured data in the visual (green, red) and near-infrared ranges, but for the land surface thermal data the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor was used rather than MODIS. VIIRS captures thermal information at a spatial resolution of 375 m and 750 m, compared to 1000 m with MODIS. Both sensors have a daily revisit time and are freely available hence data can be evaluated and downloaded directly.

DMC data was captured roughly bi-weekly and one VIIRS image per week was downloaded. In total 21 DMC and 35 VIIRS images were used in the spatial modelling from 1 October 2012 to 31 May 2013. The images used are listed in Jarmain *et al*. (2013).

4.6.4.2 Improved land surface temperatures

In the Douglas maize production area there is typically a sharp transition between irrigated pivots and the surrounding open to closed grasslands. The use of the higher resolution VIIRS data (375 m resolution) impacted less on the neighboring pixels of the fields modeled. The VIIRS data was first resampled to 300 m and then downscaled to 30 m using the sharpening tool developed by eLEAF.

Since the overpass time of the VIIRS and the MODIS Aqua sensors are very similar, data from the two sensors were compared to investigate the impact (improvement) of the higher resolution thermal information on the SEBAL outputs.

The land surface temperature captured on 10 October 2012 for some of the irrigated fields in the Douglas area using MODIS are compared to that captured with the VIIRS sensors (Figure 42). The two images were captured very close in time - 12:00 UTM for MODIS and 11:25 UTM for VIIRS. Figure 42 shows that the land surface temperature captured with MODIS was generally higher than that measured with VIIRS. This is explained by the coarse resolution MODIS thermal data (1 000 m) where adjacent, higher temperatures from dryland areas surrounding the irrigated fields, are sensed. Pixels, especially on the edges of irrigated areas and adjacent to non-irrigated areas, presented higher temperatures with MODIS data than with VIIRS (Figure 42).

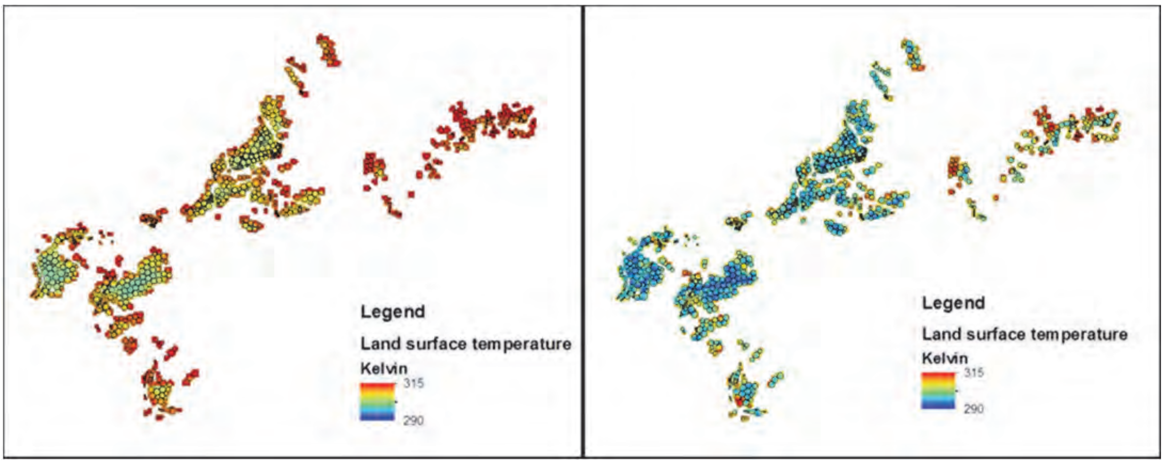


Figure 42. Land surface temperatures sensed with the MODIS Aqua sensor (left) and the VIIRS sensor (right), all resampled to a pixel size of 300 m

4.6.4.3 Meteorological data

MeteoLook was used to spatially extrapolate data from meteorological stations. Meteorological data was taken from the NOAA data base and acquired from the Agricultural Research Council (ARC) (Table 18). Weather data obtained included hourly, daily and weekly data on relative humidity, wind speed and temperature.

Table 18. Meteorological stations used in the SEBAL modelling in the Douglas area

Latitude	Longitude	Name	Code	Source
-28.8	24.76	Kimberley	68438	NOAA
-29.1	23.65	Douglas De Hoek	30892	ARC – ISCW
-29.24	23.78	Douglas Duikersvlei	30891	ARC – ISCW

4.6.4.4 Other data

A Digital Elevation Map (DEM) for the Douglas study area was again taken from SRTM.

GWK made available a shape file (Figure 33) outlining all the irrigation pivots of the Douglas area and containing information on the crop type of each pivot. This shapefile was used to extract data from the irrigated areas.

4.7 FREELY AVAILABLE ET: MOD16 DATA PRODUCT

A sample MOD16 ET image (see section 2.5.5 for a description of this product) was downloaded for the maize study area. The study area was covered by the same tile (image) that covered the sugarcane study area (h20v11). The MOD16 ET data was again first converted into 1km^2 grid cells and then re-projected. The coordinates of the field sampling points (Table 17) were then used to extract the ET data (in mm/8 days) which were converted into daily ET estimates, used in the comparison.

CHAPTER 5: WATER USE EFFICIENCY OF IRRIGATED MAIZE - RESEARCH FINDINGS AND APPLICATIONS

5.1 INTRODUCTION

In this section the accuracy of the data sets used and produced for maize is discussed and the seasonal estimates for maize summarised. The:

- SEBAL spatial estimates of canopy cover, ET, ET_{def} and biomass production are compared with field observations and estimates from well-established South African models,
- Grain yield estimates compared with combine harvester and field observations,
- Nitrogen estimates derived from satellites compared with field and laboratory observations,
- Low resolution (MOD16) ET data compared with high resolution (SEBAL) ET estimates, and
- Seasonal data related to water and crop growth, summarised for maize.

5.2 VALIDATION OF FIELD ESTIMATES OF ET, ET_{DEF} AND BIOMASS AND YIELD OF MAIZE

The SEBAL model provided spatial data, of which an example of the actual weekly and season ET is shown in Figure 43 for pivot E4. A spatial pattern is clear in both the weekly and seasonal datasets and the histogram show the spread of data values within this specific field. E.g. for field E4, the weekly ET for a week in January 2013, ranged between 30 and 60 mm across the pivot.

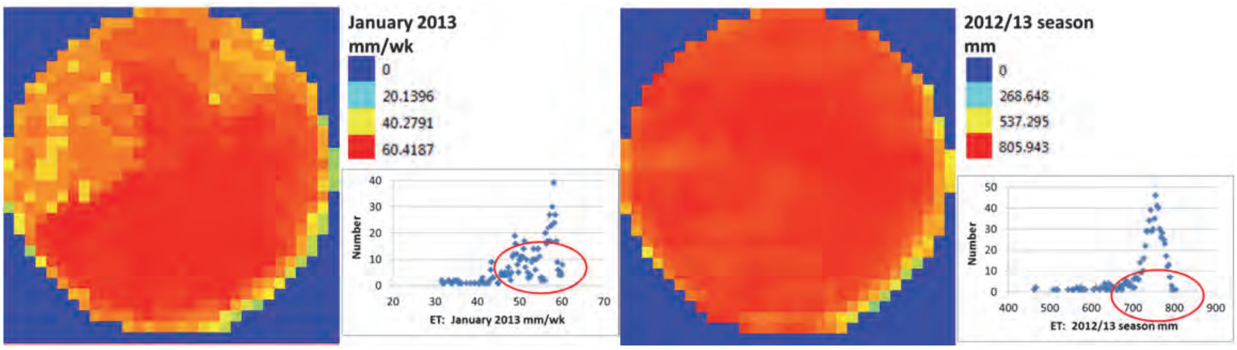


Figure 43. Evapotranspiration for one week in January 2013 and for the 2012/13 season shown spatially for field E4. A histogram showing the distribution of data (values against frequency of occurrence) is also included.

In the data assessment below, the SEBAL estimate represents information from the position in the field where the field observations were typically made.

Comparisons of the energy balance and ET data (observed and estimated) for maize, at sub-weekly intervals, are shown in Appendix IV.

In Figure 44 the SWB and SEBAL estimates of canopy cover (CC), evapotranspiration (ET), ET deficit (ET_{def}) and areal dry matter production are compared against field observations. Available SAPWAT estimates are also shown. Except for ET, only monitored in field E4, data comparisons were done for all fields (Figure 44, Appendix V). Statistical information related to the data validation for all fields are shown in Table 19. The goodness of fit is quantified with the slope and intercept of the linear regression between the estimated (Y-axis) and observed values (X-axis), as well as the coefficient of determination (R^2). Data comparisons were typically done at weekly time intervals or for dates when field observations were made.

The CC estimates from SWB and SEBAL compares well with the field observation from field E4 throughout the growing season (Figure 44). SEBAL typically exceeded the CC observations slightly for the period of partial canopy cover. For the remaining period, the SEBAL CC estimates were lower than the observations. Unfortunately field observations were not available after April to confirm the decline in CC during senescence. The general trend was that CC from SEBAL was lower than the observations (Table 19, Appendix V) (slope=0.8702, R^2=0.8018). Results from the calibrated SWB model showed that estimates of CC closely resembled the field observations (Figure 44). Considering all fields, the CC estimated with SWB agreed very closely with field observations (slope=1.001, R^2=0.8484) (Table 19). The SAPWAT CC generally exceeded the field observations by about 15 % (slope= 1.1479, R^2= 0.8613)(Table 19), with no adjustment in CC once a full canopy cover (CC=100 %) is reached in January (Figure 44), since optimal conditions are simulated.

Plotting the SEBAL ET against field observations of ET over time, shows that with the exception of a few weeks in January 2013, the SEBAL estimates exceed that observed for field E4 (Figure 44). Both the SWB and SAPWAT ET estimates were lower than the ET observed and the SEBAL ET for the period of incomplete CC at the beginning of the season, until about 24 January 2013 when this trend reversed and the ET estimates exceeded the observations. Considering data from all fields, the linear regressions fitted showed that all ET estimates were lower (6 to 20 %) than that observed in field E4 (Table 19), with the SEBAL fit (R^2=0.8074) slightly better than SWB (R^2=0.7265) and SAPWAT (R^2=0.7855).

Comparing the SEBAL ET estimates to the current ET estimates that GWK uses in their irrigation recommendation (based on longterm ET_o data) (Figure 45), it is clear that this estimate (k_cET_o(old)) was lower than the SEBAL estimate for the period of incomplete CC (or until around 24 January), where after it mainly exceeds the SEBAL estimate of and the observed actual ET. The newly proposed ET estimates to be used by GWK (based on work by Snyman, 2011) (k_cET_o(new)) compare better with the SEBAL and field estimates. The new k_c values were derived for genetically modified maize cultivars grown in the Riet River irrigation scheme, over a period of five growing seasons (2003-2007) (Snyman, 2011).

Lastly, the GWK recommendation for irrigation is also compared to the SEBAL ET estimates (Figure 45). This value take into account the estimates of ET (or k_cET_o(old)) as well as any soil water content shortfall from within set boundaries. The GWK recommendation is hence shown to exceed the actual ET from the point of roughly complete CC until the end of the growing season (Figure 45), with this trend suggesting that the farmer was falling behind with irrigation applications.

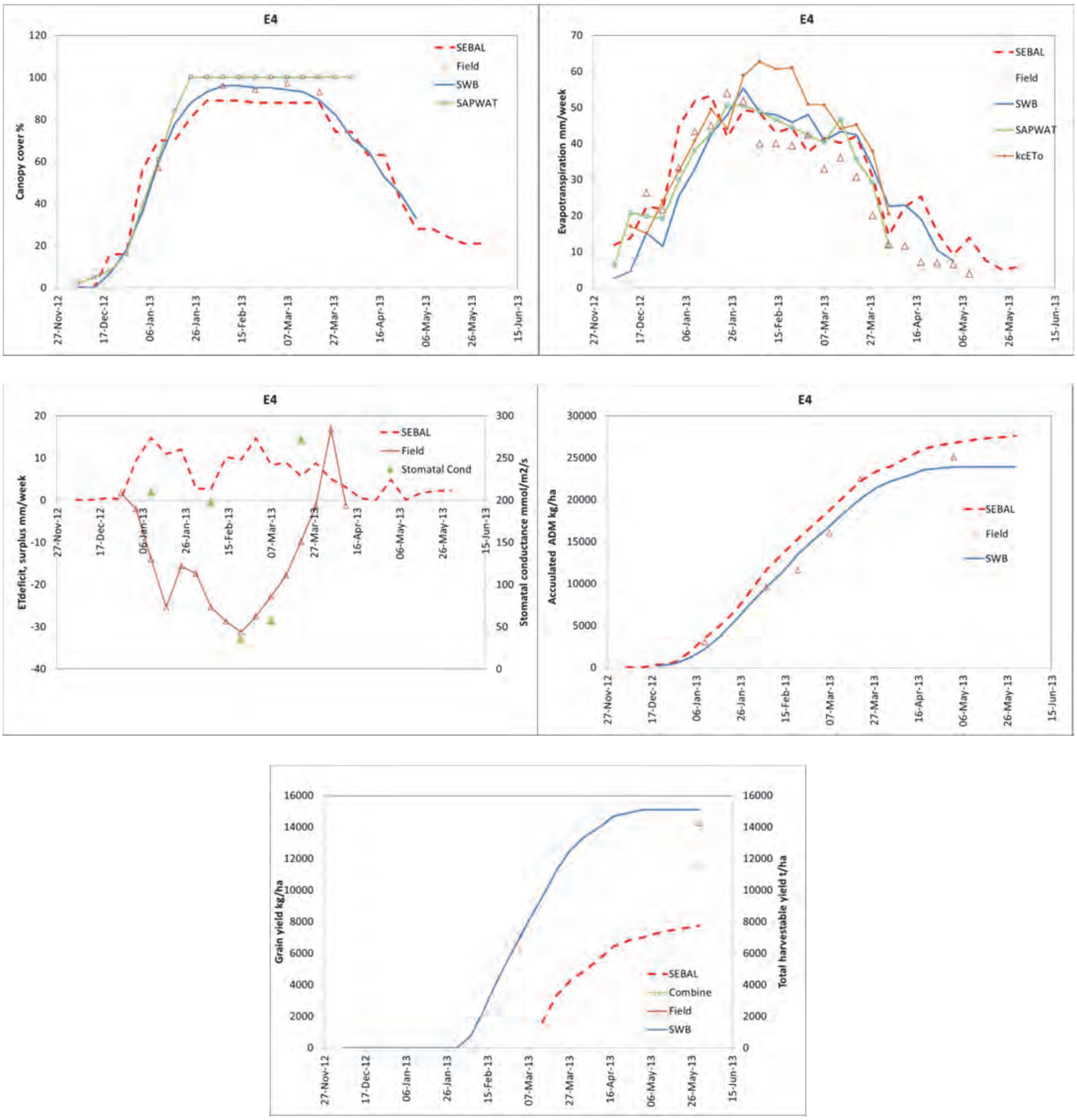


Figure 44. Comparisons of Canopy cover (CC), Evapotranspiration (ET), Evapotranspiration deficit (ET_{def}) and Areal Dry Matter (ADM) observed and compared to estimates with SEBAL, SWB and SAPWAT (where data was available) for field E4. Yield estimates from SWB and field observations representing grain plus cob mass are also shown together with average SEBAL and combine harvester estimates of grain mass only.

Areal (or above ground) dry matter from SEBAL and SWB followed the trend of the field observations in field E4, with the SEBAL estimates exceeding the other estimates (Figure 44). Interesting to note is the close agreement between the field observation and the SEBAL estimates in March, but the lower final biomass field observation. This could possibly suggest that the SEBAL assumption regarding the biomass partitioning in roots, may not remain constant. Considering the linear regression applied to data from all the fields, the SEBAL ADM estimates agreed better with the field observations (slope= 0.9938, R^2= 0.9333) than the SWB estimates (slope= 0.9292, R^2= 0.9496) (Table 19).

The ET_{def} from SEBAL was compared to the soil water content surplus or deficit estimated within each field using neutron probe data. An ET_{def} in SEBAL refers to an ET shortfall from potential ET whereas a soil water content deficit refers to a soil water shortfall from the lower limit of soil water content, set for that specific field and soil. Field E4 shows clearly that whenever an ET_{def} was estimated for the field, similarly, there was a soil water content related deficit (more negative value). Periods of lower ET_{def} and soil water content deficits also mainly coincided with higher stomatal conductance observed (Figure 44). This trend was also observed in the other fields (Appendix V).

Observed dry yield and SWB yield (both representing cob plus grain mass) were compared with the SEBAL grain estimate and the combine harvester dry grain estimate (Figure 44). The SEBAL grain estimate was calculated from ADM, from the day of flowering. The field observed yield compared well with the SWB yield estimates since both represent the cob plus grain mass and since SWB was calibrated to the observed yield. Both these estimates exceeded the average combine harvester and SEBAL grain yield estimates, which were very similar.

A number of general observations related to the other fields (Appendix V), where field observations were compared to estimates from other models, include:

- Canopy cover: the SEBAL CC estimates consistently exceed the field observations whilst an incomplete canopy cover exists. After that point the SEBAL CC remains lower than the SWB estimate and the field observations. It appears as if differences in CC between fields were more clearly estimated with SEBAL compared to the other methods.
- Evapotranspiration: SEBAL ET typically exceeded other ET estimates (SWB, SAPWAT) throughout the season. The ET estimate applied in the past by GWK (k_cET_o(old)) however exceeded the SEBAL ET estimate in peak of the growing season. Also, the very high SAPWAT ET estimates at the beginning of the season (prior to complete CC) needs to be investigated, but probably represent soil evaporation.
- Evapotranspiration deficit: The SEBAL ET_{def} corresponds well with periods of soil water deficit based on Neutron Water Meter data. The exception is field F11 which needs to be investigated, since it appears as if the surplus should be a deficit. Also, the higher SEBAL ET_{def} often agrees with lower observed stomatal conductance.

Table 19. Summary of validation results for 7 maize fields. The goodness of fit of is quantified with the slope and intercept of the linear regression between the field observed and estimated values, as well as the coefficient of determination (R^2).

	SEBAL			SWB			SAPWAT/Combine[45]		
Variable	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Canopy cover (%)	0.8702	0.8172	0.8018	1.001	-3.6687	0.8484	1.1479	-9.9084	0.8613
ET (mm/week)	0.7919	11.212	0.8074	0.8456	7.7815	0.7265	0.9352	4.0475	0.7855
Biomass (kg/ha)	0.9938	1311.8	0.9333	0.9292	827.13	0.9496			
Dry yield (kg/ha)[46]	-0.8325	18.114	0.7835						

[45] Combine refers to the combine harvester.

[46] Yield with 0 % moisture. Data from field A3 not included. SWB and observed yield refers to the total dry above ground harvestable yield (grain plus cobs). SEBAL and combine harvester yield refer to dry grain yield only.

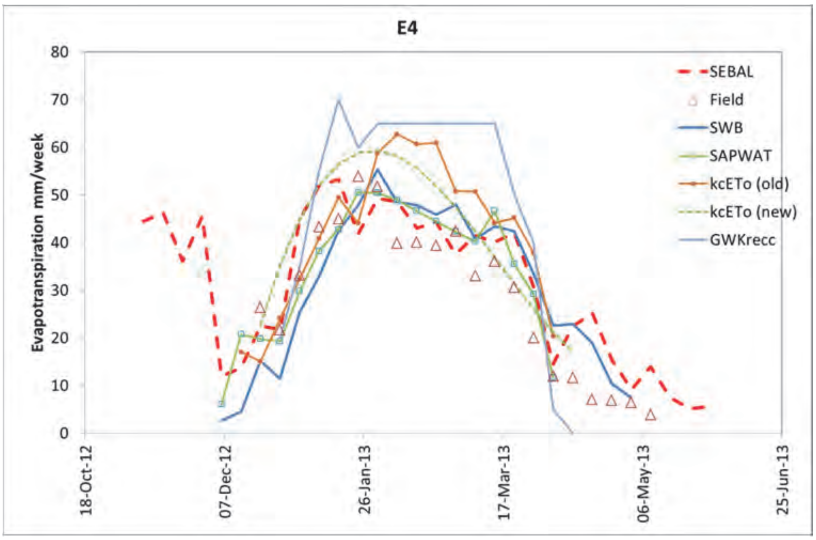


Figure 45. Evapotranspiration estimates at a weekly interval estimated with various methods as well as observed in the field. k_cET_o(old) and k_cET_o(new) refers to the ET estimates GWK includes in the estimation of the ET (irrigation) recommendation (GWK_{recc}) for each week.

5.2.1 Coarse resolution ET estimation with MOD16

The capture periods of the MOD16 ET and SEBAL data products differed hence a 8-day estimate for MOD16 was converted to a daily average ET and similarly the SEBAL weekly estimate, into a daily ET. Figure 46 shows the MOD16 ET data for the week ending 26 March 2012 in relation to the SEBAL data (data insert). Note the use of the same scale.

Generally the MOD16 converted daily ET data was lower than the SEBAL ET estimates. For four specific MOD16 pixels containing maize and shown in Figure 46 (within the black square), the MOD16 ET estimates were within the estimated SEBAL ET range, but the MOD16 ET was typically 10 to 50 % lower than the average SEBAL estimate for that specific pixel (Table 20). Although the irrigated areas can be detected in the MOD16 data from the higher ET estimates, the spatial resolution is too low to show in-field variability as shown in the SEBAL data (Figure 46). It should be noted that the 1 km^2 MOD16 pixel shows the mean value for the entire pixel with all vegetation. For the SEBAL data non-agriculture has been masked out and a value of zero attributed. Hence, if one would compare the SEBAL ET for the irrigated agriculture plus its surrounds from within a specific MODIS pixel, it may be more comparable.

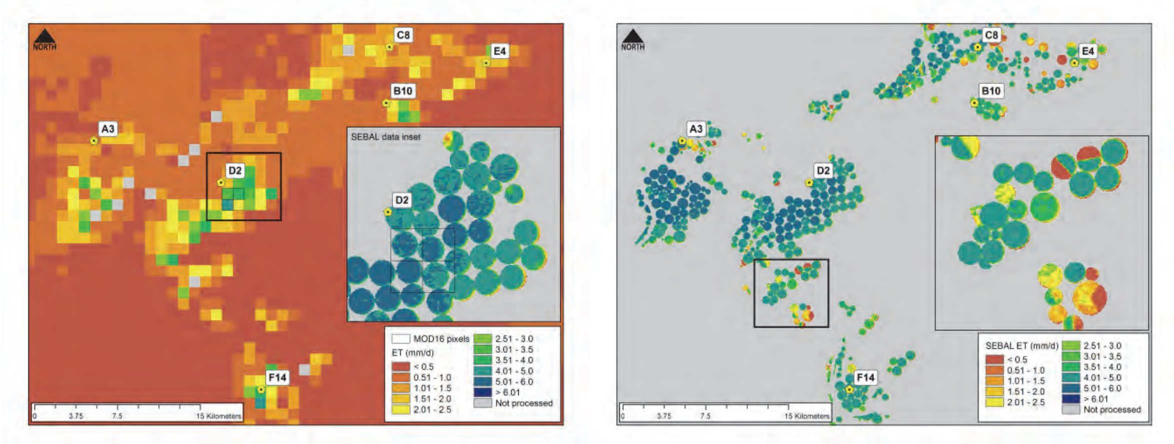


Figure 46. MOD16 data at a 1km resolution for the week ending 26 March 2012 across the maize study area together with SEBAL 30m spatial resolution data for the same area (right). The insert in the left image shows the four specific pixels referred to in Table 20.

Table 20. MOD16 ET data (converted mm/d values) compared to SEBAL daily ET values. Included is the amount of SEBAL (pivot) pixels present in each MOD16 pixel from the insert in Figure 46. The four MOD16 pixels are taken from Figure 46, representing the four selected pixels clockwise, from top left.

MOD16 pixel no.	MOD16 ET mm/d	No of SEBAL cells with data	SEBAL MIN mm/d	SEBAL MAX mm/d	SEBAL RANGE mm/d	SEBAL MEAN mm/d	SEBAL STD mm/d
1	3.29	785	3.11	5.40	2.30	4.93	0.32
2	3.81	915	3.19	5.70	2.51	5.00	0.36
3	2.41	858	2.81	5.42	2.61	4.79	0.36
4	4.63	837	3.27	5.58	2.31	5.13	0.42

5.3 VALIDATION OF FIELD ESTIMATES OF THE GRAIN YIELD

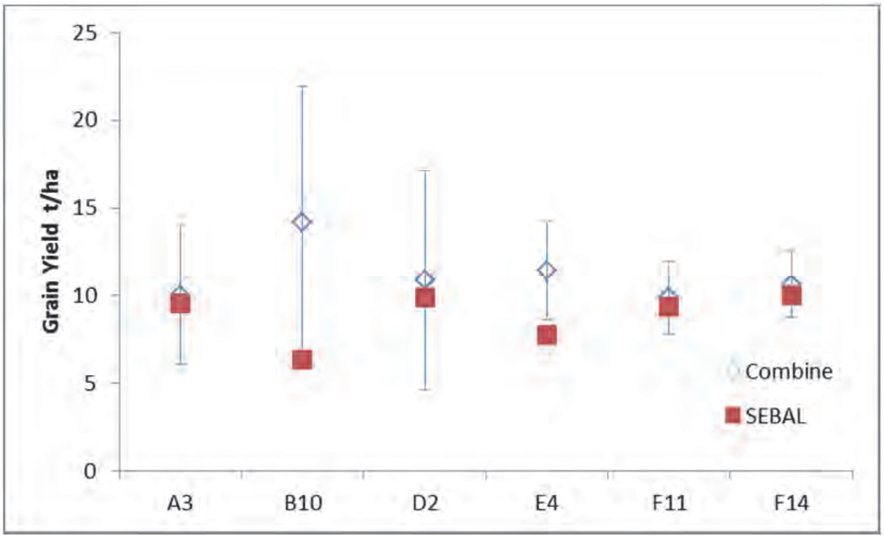
5.3.1 Grain yield as a function of accumulated dry matter (flowering to harvest)

The combine harvester yield (grain) data was corrected to 0 % moisture and the average estimate across the field was used as (reference) yield observation. The field observed yield included both the grain and cob mass as did SWB and these two estimates were hence compared.

Since SEBAL does not estimate grain yield directly, the grain yield was estimated from the ADM (accumulated ADM from flowering to crop harvest). The average SEBAL C4 ADM per field was used in the calculations. Flowering occur around 75 to 80 days after planting in the Douglas area (GWK, personal communication). Estimates of SEBAL grain yield from this approach were compared to the combine harvester dry grain yield estimates (averaged over the field). The standard deviations in the combine harvester yield estimates per field are also shown.

SEBAL grain yield compared well with the average combine harvester observations for fields A3, D2, F11 and F14 (Figure 47). However, large differences existed for fields B10 and E4, although the combine harvester standard deviations in the grain yield for these fields, explained the differences (Figure 47). It is possible that flowering was initiated earlier in these two fields (prior to 75 days after planting).

Fitting a linear regression to the observed and SEBAL grain yield estimates yielded an inverse relationship with R^2=0.7835, slope=-0.8325 and offset=18.114 (Figure 47). The negative slope (-0.8325) shows that the SEBAL average grain yield estimates typically decreased as the yield observed by the combine harvester increased (Figure 47). Because of the small sample set, this relationship is greatly affected by two outliers (B10 and E4) and if removed the relationship changes substantially (slope=0.6264; offset=3.2088; R^2=0.8849).



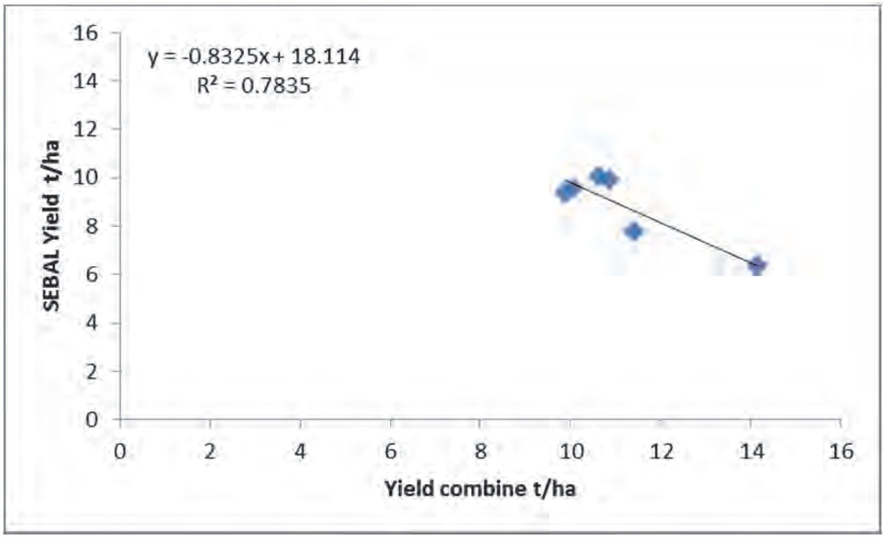


Figure 47. (*top*) The observed average grain yield from the combine harvester (plus standard deviation) and the SEBAL estimated grain yield, plotted per field. The SEBAL estimate was obtained by accumulating ADM from flowering to harvest. (*bottom*) Observed combine harvester yield plotted against the SEBAL yield estimate. Combine harvester data was not available for field C8.

Comparing the (total above ground) harvestable yield (grain plus cob yield) determined in the field and estimated with SWB to the grain yield from the combine harvester and SEBAL, show that with the exception of fields A3 and B10, the total harvestable yield estimates always exceeded the grain yield estimates (Figure 48), by 5 to 30 %. In these two fields, the combine harvester grain yield estimates showed a large variation around the mean.

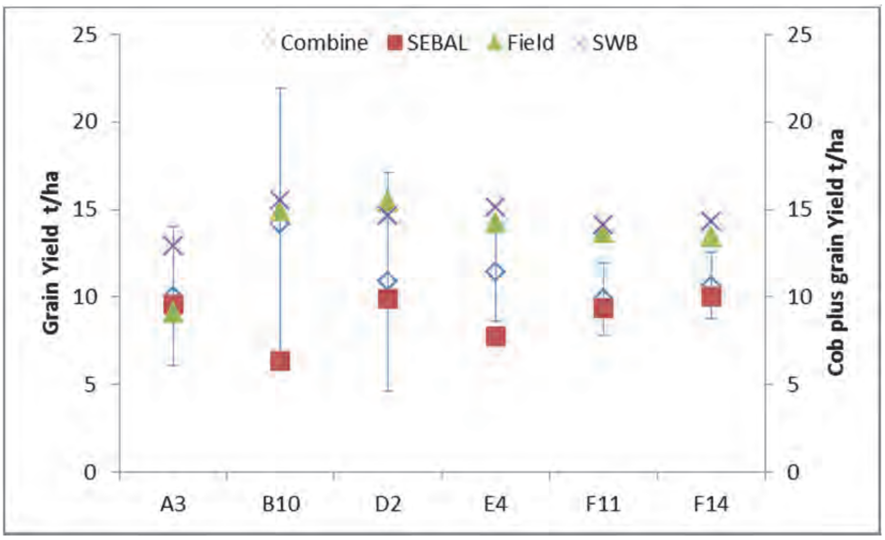


Figure 48. The observed average grain yield from the combine harvester (plus standard deviation) and the SEBAL estimated grain yield plotted for each field. The SEBAL estimate was obtained by accumulating ADM from flowering to harvest. The total harvestable yield (cob plus grain) observed in the field and estimated with SWB is also shown. Combine harvester data was not available for field C8.

Other indicators of flowering (or vegetative growth cessation) which could possibly be used in the yield calculations were also investigated, instead of a fixed date after planting. These included NDVI and albedo. Although fairly abrupt changes in the NDVI and albedo were visible around certain dates (Figure 49), which indicate a change in maize canopy conditions no clear conclusions could be drawn ito using a specific value to initiate ADM accumulation. For example around 98 days after planting there was an increase in albedo as well as a decrease in NDVI (Figure 49), suggesting a change “colour” of the surface as well as a change in growth vigour.

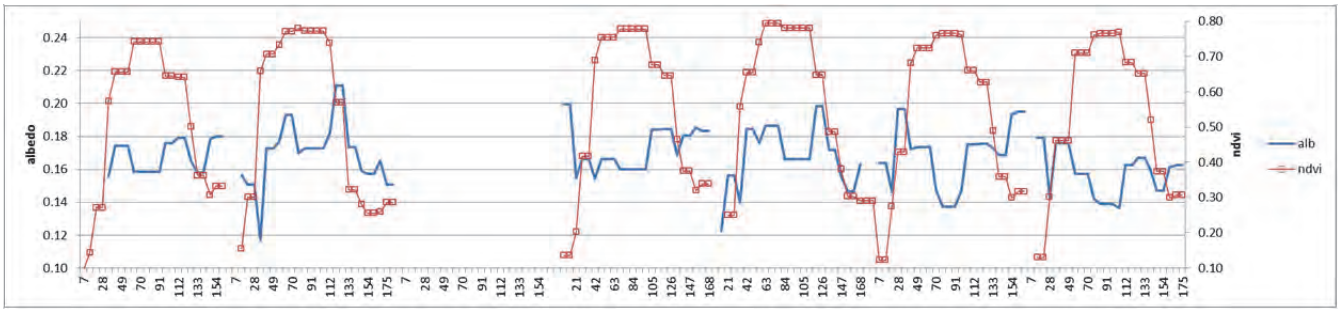


Figure 49. NDVI and albedo from SEBAL, plotted for six maize fields against days after planting (X-axis)

5.3.2 Harvest indices

The harvest index (HI) for each field was calculated from the combine harvester data and the accumulated SEBAL C4 ADM estimate per field. Harvest indices were calculated using combine harvester grain yields with and without moisture (0 %). Typically grain is harvested and delivered to silos at a moisture content of 12 %.

The harvest indices based on a 0 % grain moisture content ranged between 0.39 and 0.57, with an average of 0.45 (Figure 50). The range in HI of 18 % illustrates a range of conditions were experienced between the fields which affected the varying harvests. The reasons for the higher HI of B10 could be general good water management, but this cannot be confirmed. The field with the lowest harvest index F11 could have experienced water stress during the critical phase around flowering or other factors (salinity or pests or diseases) could have affected the yield from this field. This illustrates that the use of a fixed harvest index to estimate grain yield is not favoured since it does not include a stress factor. Figure 50 also shows the harvest indices estimated with a moisture content of 12 % to range between 0.44 and 0.64.

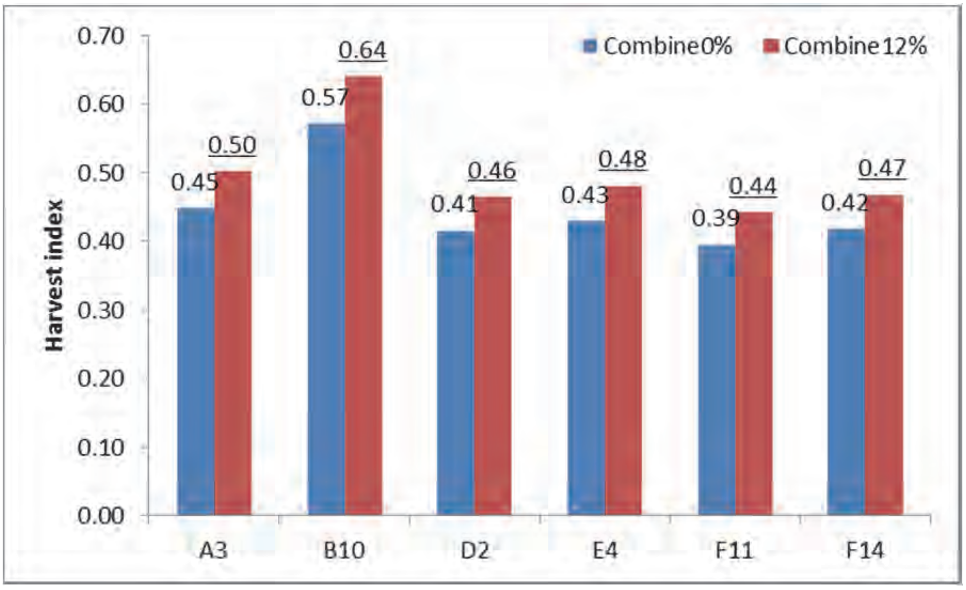


Figure 50. Harvest indices (HI) estimated for each field. The HI was estimated as the ratio of grain yield from the combine harvester (average per field) to the accumulated C4 ADM estimated with SEBAL (average per field). Combine harvester data was not available for field C8. Combine0% refers to HI calculated from grain estimates with 0 % moisture. Combine12% represents HI calculated with grain estimates with 12 % moisture content.

5.4 ACCURACY OF ESTIMATES OF NITROGEN IN MAIZE

Leaf N was measured in the field with the SPADOMETER and analyzed in the laboratory as N percentage of leaf dry matter. Additionally, the canopy N (kg/ha) was estimated for all the maize fields from satellite data. Figure 51 presents the weak correlation between N percentage and SPADOMETER reading for the same leaf with a R^2 of 0.56. This is consistent with previous GWK observations (Haarhoff, 2014).

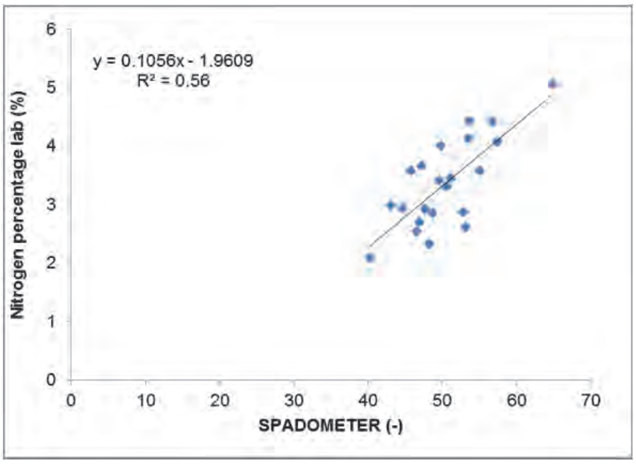


Figure 51. Relationship between in-field SPADOMETER readings and analyzed leaf nitrogen percentage for the youngest fully development leaf. Data is taken from the 7 maize fields studied.

The canopy N content (kg/ha) estimated from satellite data was compared with leaf N (%) by estimating the N in the leaves and dividing it by the estimated dry matter of the leaves. The ADM for maize is known in this project and the partitioning of ADM to leaves was estimated to be 35 %. This ratio was taken to partition the canopy N content to leaf N content. [This fraction is known from field experiments in SA for sugarcane, where a fraction of 0.65 was used for nitrogen partitioning to cane and 0.35 to leaves. The same fraction was assumed for maize, both being from the C4 grass family (*Poaceae*) and having similar carbon fixation]. Figure 52 shows that dry biomass production of leaves increased during the vegetative stage but ended at flowering (tasseling) on 6 March 2013. The satellite derived N showed an increase from 5 to 60 kg/ha for the first month, where after N ranged from 40 to 60 kg/ha and decreased to 25 kg/ha after tasseling. This reduction is expected due to the movement of nutrients into the production of flowers.

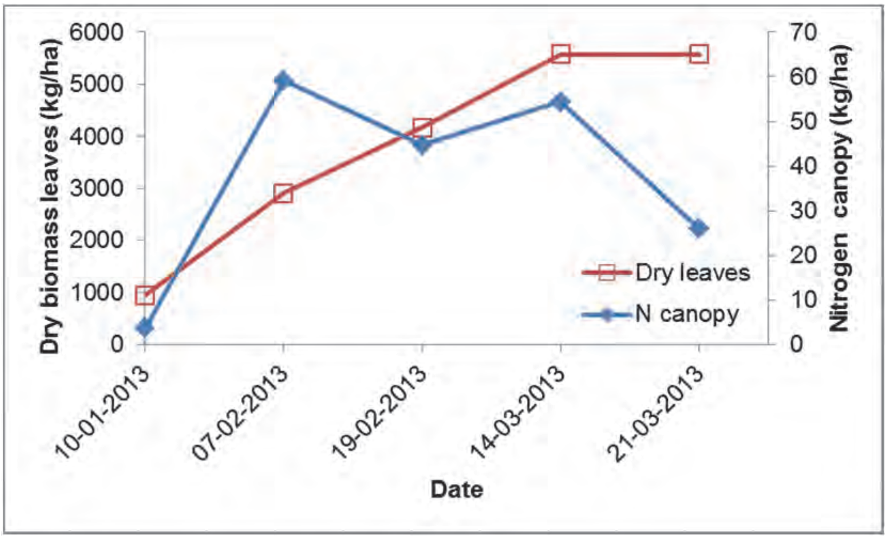


Figure 52. Calculations of dry biomass for leaves (kg/ha) and nitrogen canopy (kg/ha) based on satellite data

The nitrogen percentage was estimated as the percentage of nitrogen from the total dry matter for leaves. Figure 53 shows the nitrogen canopy percentage and laboratory analyzed leaf nitrogen percentage. The values of nitrogen canopy percentage and laboratory leaf nitrogen percentage followed a similar trend from February onwards. The difference in the first part of the season can be explained because the canopy cover is not fully developed and the satellite will capture information from a combination of soil and vegetation, at pixel level. In general, the nitrogen canopy percentage estimates were lower than the laboratory N percentage. This can partly be explained because the laboratory samples included only the youngest fully development leaves. Nitrogen translocates to younger leaves which are more actively photosynthesizing. Older leaves thus have lower N concentrations. The spatial model takes all leaves into account.

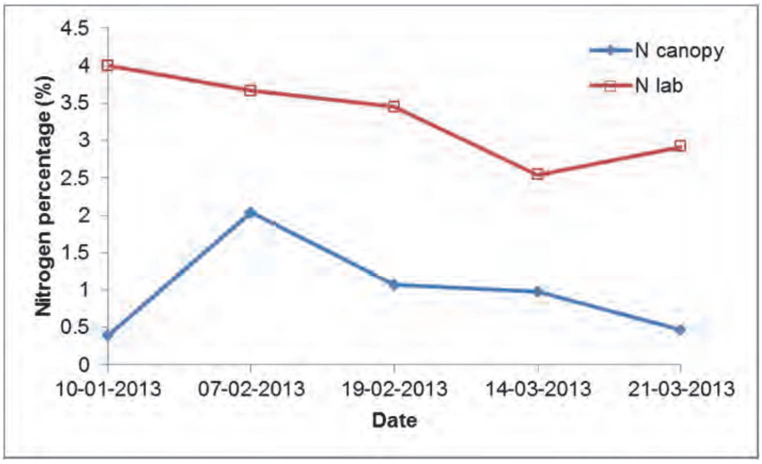


Figure 53. Canopy nitrogen percentage (Ncanopy) and laboratory leaf nitrogen percentage (Nlab)

Figure 54 presents the correlation between nitrogen canopy percentage and laboratory nitrogen percentage for several maize fields excluding the data for the month of January. This was done to exclude the data that includes a background effect of the soil, prior to full canopy development. The data correlation was poor with a R^2 of 0.46. This can be explained in part by the following: (a) the laboratory analyses represent information from a number of samples only within a pixel of 30 m x 30 m and hence this N estimate do not represent the entire pixel or field, (b) the nitrogen canopy percentage represent an average for the entire field, averaging out the spatial variation, (c) the laboratory nitrogen percentage includes data from only the youngest fully development leaves whereas the spatial canopy nitrogen estimate, includes N percentages from both young and old leaves. Figure 55 presents the satellite estimated spatial variability of canopy N (kg/ha) in a single field. The N values across this field ranged: from 30 to 60 kg/ha.

These spatial estimates of canopy nitrogen can possibly be used in a strategic way over subsequent seasons to identify areas with N deficiency issues and relate this information with the dry biomass of leaves to assess the nitrogen canopy percentage. In the Douglas region, six application of N for maize is typical, with four applications in the first 6 weeks after planting and the remaining two applications around tasseling and grain filling. Frequent N information, with a spatial dimension will allow the farmer to respond to nitrogen shortages before tasseling and during grain filling.

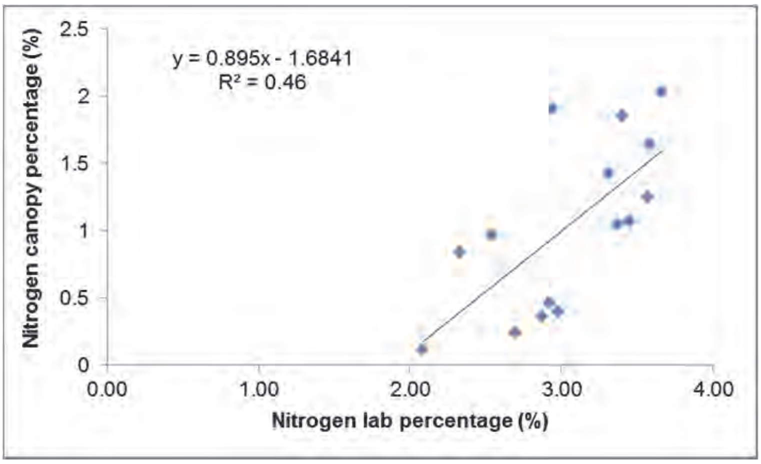


Figure 54. Relationship between the canopy nitrogen percentage and laboratory nitrogen percentage

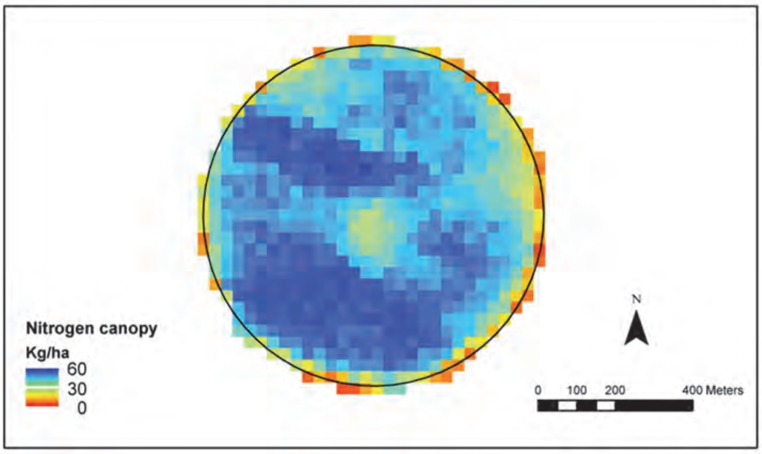


Figure 55. Canopy Nitrogen for a specific field in kg/ha

5.5 SEASONAL ESTIMATES OF MAIZE ET, ET_{DEF}, BIOMASS PRODUCTION AND WATER USE EFFICIENCY

The seasonal statistics for maize are summarised in Table 21. The statistics are based on data from an area of approximately 13 500 ha under maize during the 2012/13 season.

Table 21. Seasonal statistics of evapotranspiration (et), Evapotranspiration deficit (ET_{def}), biomass (BIO) and biomass water use efficiency (WUE_{bio}) estimated for maize for the 2012/13 season

	ET [mm/season]	ET_{def} [mm/season]	BIO [t/ha/season]	WUE_{BIO} [kg/m^3]
Mean	692	75	25	3.5
Stdev	118	41	6	0.5

5.5.1 *Evapotranspiration (ET)*

Seasonal ET for maize produced in the Douglas area was estimated for the 2012/13 summer season, spanning from 7 December 2012 to 28 May 2013, a period of 173 days. Figure 56 shows season ET spatially for the study area and Figure 57 presents the ET histogram for pixels with maize. The accumulated seasonal ET ranged from 600 to 800 mm/season for the majority of the maize fields (Figure 57). This accumulated ET was fairly evenly distributed. ET estimates along or towards the Orange River (Figure 34) seems to generally exceed ET estimates along other river reaches.

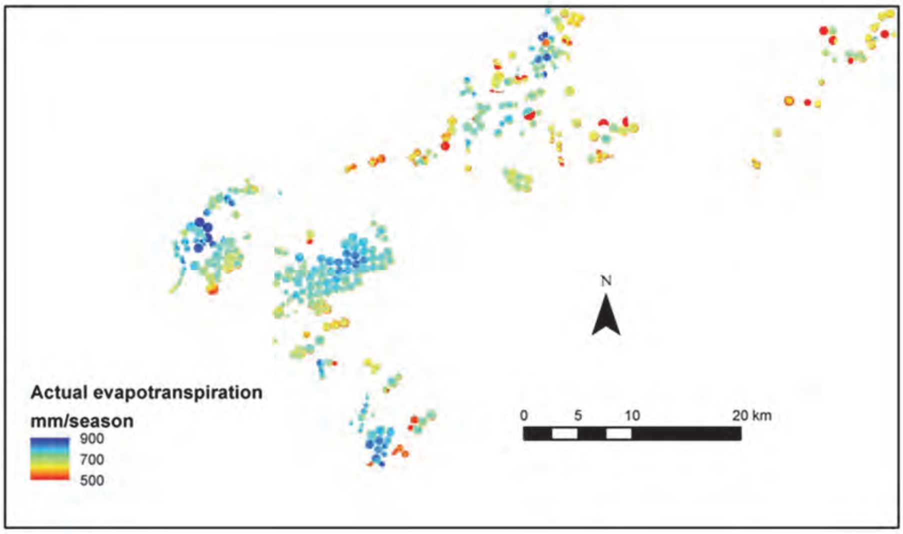


Figure 56. Seasonal actual ET from SEBAL for maize fields for the growing season (7 December 2012 to 28 May 2013)

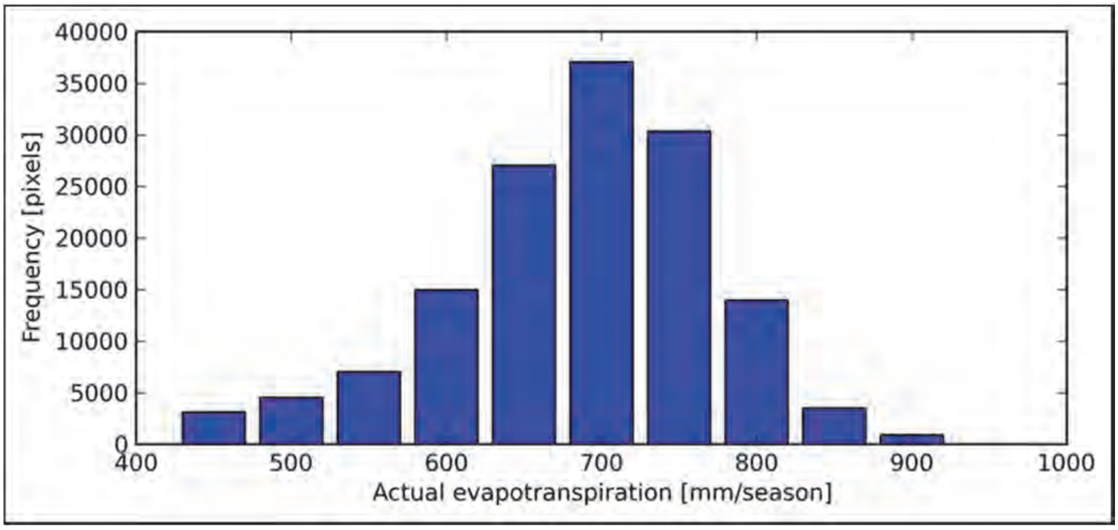


Figure 57. Histogram of ET for pixels from maize fields for the growing season (7 December 2012 to 28 May 2013)

5.5.2 *Evapotranspiration deficit (ET_{def})*

Figure 58 shows the spatial distribution of accumulated ET_{def}. ET_{def} values between 0 and 100 mm were evenly distributed in the region. There are some areas in the eastern region with values of 200 to 300 mm/season which indicates an ET_{def} in the order of 1.1 mm/day for the growing season. The ET_{def} values between 30 and 80 mm/season were frequent, as shown in the histogram (Figure 59). This equate to a water shortage of less than 0.5 mm/day. In general, the region has good irrigation infrastructure which resulted in typically low ET_{def} during the growing season.

In the seven maize fields studied, the SEBAL ET_{def} estimate was typically 5 to 20 % of the total seasonal ET or 41 to 151 mm, which suggests large differences in irrigation applications and water stress conditions experienced in the fields.

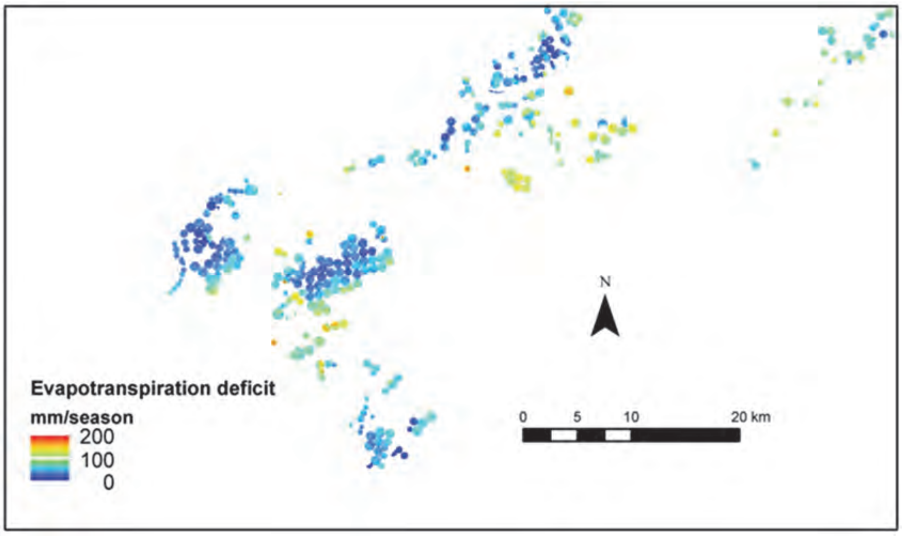


Figure 58. Seasonal ET deficits for all maize fields for the growing season from 7 December 2012 to 28 May 2013

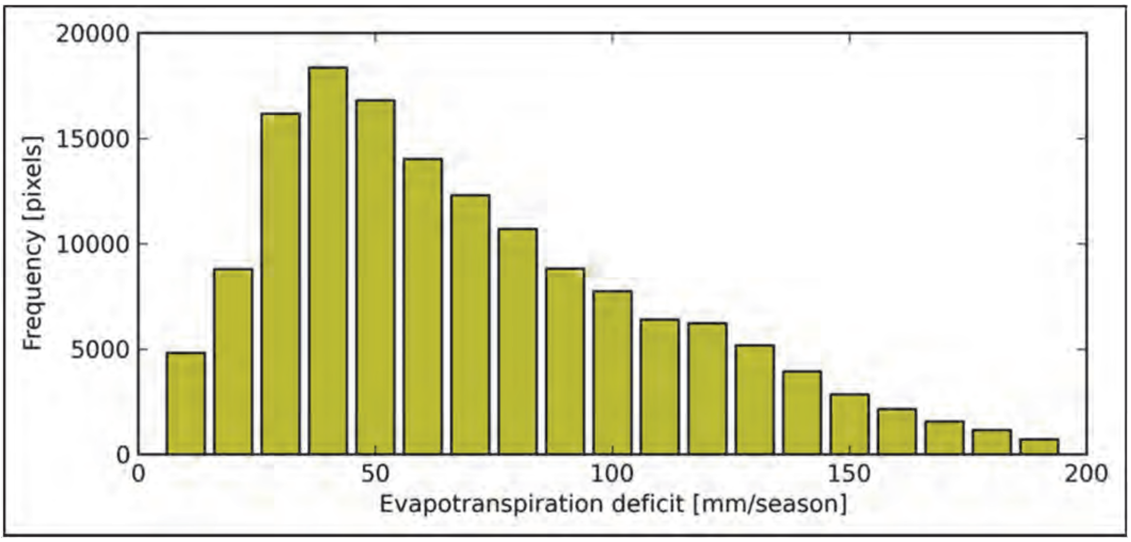


Figure 59. Histogram of ET deficit for maize fields for the growing season (from 7 December 2012 to 28 May 2013)

5.5.3 *Total biomass production*

The actual biomass production includes total (below plus above) dry biomass production for this C4 crop. Fields with high biomass production (20 to 30 t/ha/season) are distributed across the area (Figure 60). However, there are some pivots with actual biomass values ranging between 10 and 20 t/ha/season. The lower biomass estimates appeared mainly along the Riet River. The lower biomass production can be related to pests and diseases, over irrigation, salinity and soil compaction or cultivar differences. The majority of the pixels for maize fields have SEBAL biomass production values ranging between 22 and 30 t/ha/season as shown in Figure 61. The range in biomass production suggested that improvements in production are possible.

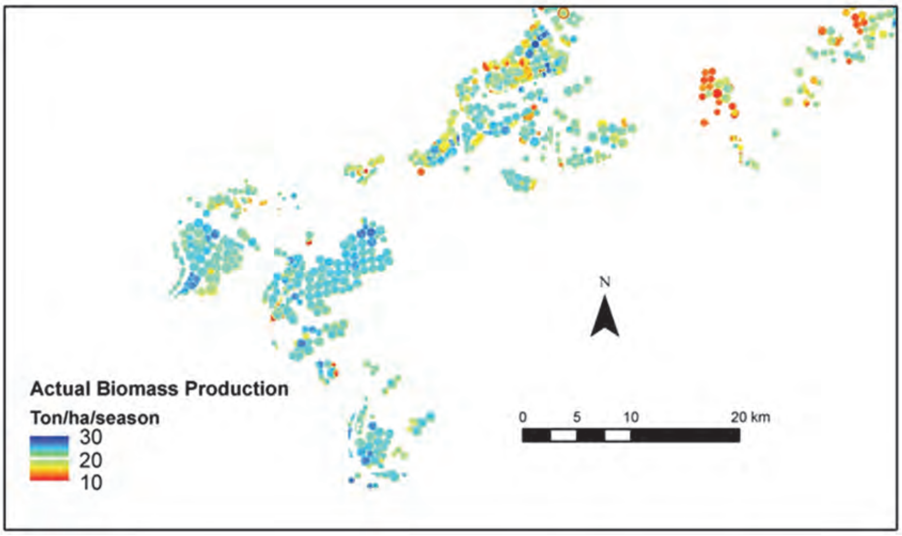


Figure 60. Actual biomass production for maize fields for the growing season from 7 December 2012 to 28 May 2013

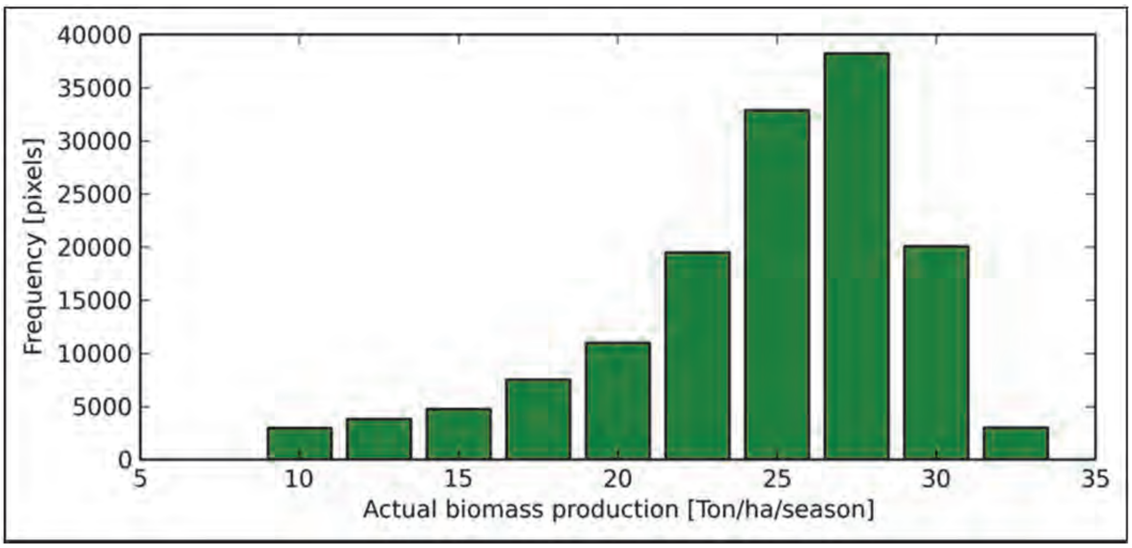


Figure 61. Histogram of actual biomass production in maize fields for the growing season from 7 December 2012 to 28 May 2013

5.5.4 *Biomass water use efficiency (WUE_{BIO})*

The BWUE ranged between 1 and 4 kg/m^3 (Figure 62, Figure 63). The WUE_{BIO} values in the western region were in the order of 2 kg/m^3 and in other areas in the order of 4 kg/m^3. Although these differences appear to be low, it relates to considerable differences in the use of water. For the production of 20 t dry biomass during the growing season, the fields in the western region will require 10000 m^3 whereas other fields will use 5000 m^3.

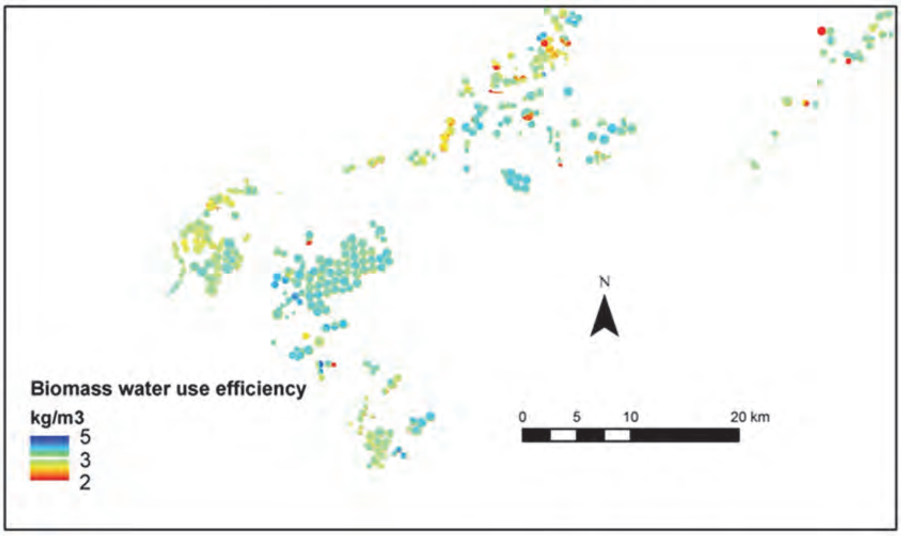


Figure 62. Biomass water use efficiency for maize fields for the growing season from 7 December 2012 to 28 May 2013

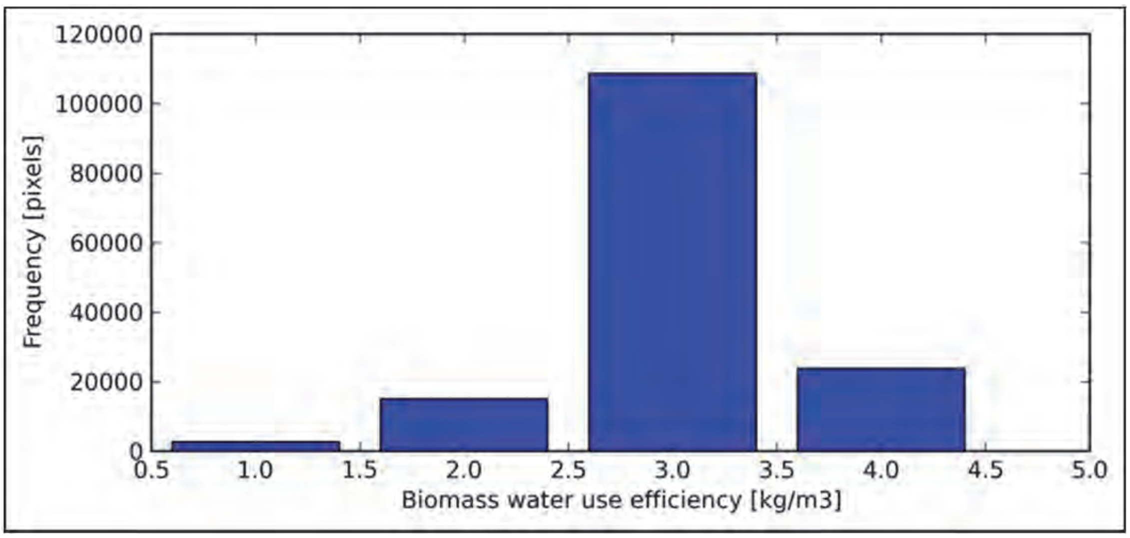


Figure 63. Histogram of biomass water use efficiency for maize fields for the growing season from 7 December 2012 to 28 May 2013

5.5.5 Water use efficiency

The water use efficiency, taking into account grain yield (WUE_{GRAIN2}), was estimated for six of the fields studied. The combine harvester yield (average) ranged between 9.9 t/ha and 14.1 t/ha (Figure 64). Combining the combine harvester data, with the SEBAL ET yielded water use efficiencies ranging between 1.28 kg/m^3 (field F11) and 1.91 kg/m^3 (field B10) where the SEBAL ET estimates were used (Figure 64). Interesting to note is that the highest WUE was estimated for the field which achieved the highest yield, and *vice versa* (Figure 64).

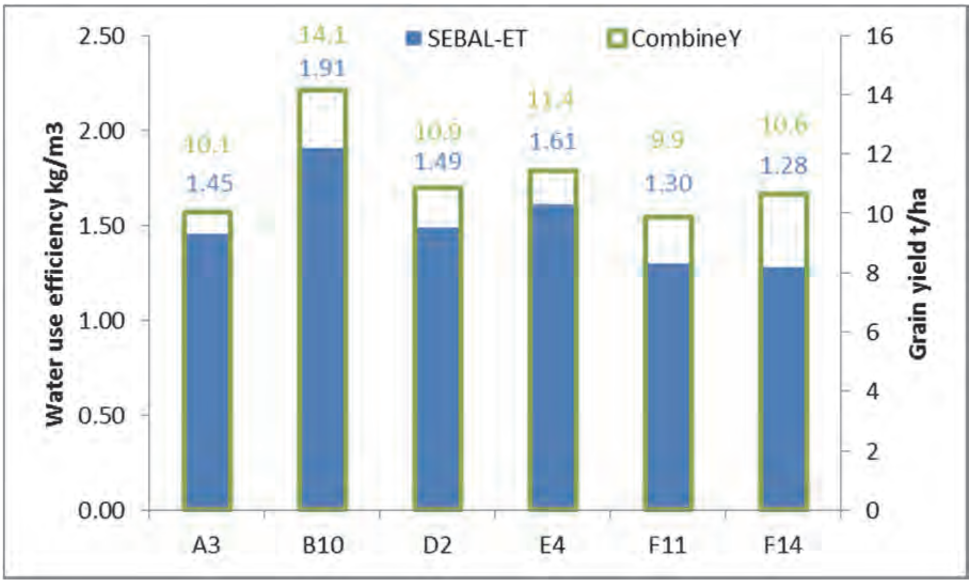


Figure 64. The WUE estimated for the six maize fields studied, shown with the yield estimates from the combine harvesters. Seasonal SEBAL ET and harvestable yield estimates were used in the estimation.

CHAPTER 6: CAPACITY BUILDING AND TECHNOLOGY TRANSFER

6.1 FORMAL TRAINING OF INDIVIDUAL STUDENTS

Students from a number of Universities have been involved in this project, from BSc to PhD level. These students are listed in Table 22 together with the status of their studies.

Table 22. List of students formally involved in the project and registered for a degree

Name	Degree	University	Nationality	Supervisor	Status
Ernesto Bastidas-Obando	PhD	TU Delft	Columbian	W Bastiaanssen	In progress
Aresti Paraskevopoulos	MSc	University of KwaZulu-Natal	South African	A Singels, A. Senzanje	To be submitted and completed in 2015
Mpendulo Dlamini	MSc	University of Pretoria	Swazi	J Annandale, M vd Laan	To be submitted 2014
David Taverna-Turisan	MSc	University of Pretoria	South African	J Annandale, M vd Laan	To be submitted and completed in 2014
Letlotlo Mokoma	BSc	University of the Free State	South African	S Walker, C Jarmain	To be submitted and completed in 2014
Max Bhula	BSc Hons	Stellenbosch University	South African	A van Niekerk, C Jarmain	To be submitted and completed in 2014
Arne Esterhuizen	BSc Hons	Stellenbosch University	South African	B vd Merwe	Graduated in 2013
Carl Cloete	BSc Hons	Stellenbosch University	South African	Z Munch	Graduated in 2013

Cloete C. 2012. The use of remote sensing products for water use management in irrigated sugarcane crops in the Incomati river basin. Final Research Report submitted in partial fulfilment of the requirements for the degree Honours Baccalaureus (Geoinformatics), Stellenbosch University. 50 pages.

Esterhuizen A. 2012. Agriculture @ Android. Final Research Report submitted in partial fulfilment of the requirements for the degree Honours Baccalaureus (Computer Science), University of Stellenbosch, 18 pages.

6.2 IN-FIELD TRAINING COURSES FOR STUDENTS

Two in-field training courses were presented as part of this project, to expose different students to the field technologies used to estimate water use efficiency and evaluate the accuracy of the spatial technologies and estimates.

Training event 1

An in-field training course for post-graduate students took place from 24-27 July 2012 on a commercial farm in the Komatipoort area. Lecturers and students from University of Pretoria and University of KwaZulu-Natal were involved in the training course and a total of 23 people attended this training.

The aim of the in-field training course was to expose students to methods used to estimate water use efficiency of irrigated sugarcane and which are used in this research project to evaluate both field and spatial modelling estimates. During the four days the focus was on (a) estimating ET, (b) soil moisture, (c) weather station calibration, (d) biomass sampling and (e) plant physiological measurements. Researchers from UP, UKZN and SASRI assisted with the various sessions (Figure 65).

Details on this training event are provided in Jarmain (2012b).

Figure 65. ***top*** **Staff from UKZN, SASRI and UP involved in the first in-field training course;** ***bottom*** **UKZN and UP Staff and students from various institutions involved in the second in-field training course**

Training event 2

The second training event took place from 6 to 13 April 2014 at Citrusdal. This training event coincides with a detailed measurement field campaign as part of the WRC project K5/2275//4 'Quantifying citrus water use and water stress at tree and orchard scale'. Post-graduate students from the University of Pretoria, Stellenbosch University and the University of Western Cape attended the training course. The training focused on measurements of ET, transpiration, stem and leaf water potential, stomatal conductance, soil evaporation and soil moisture. The students "shadowed" the post-graduate students for full day cycles of a specific technology and rotated between all the technologies.

6.3 REMOTE SENSING AND HYDROLOGY TRAINING COURSE FOR STUDENTS

Two training courses were presented to expose students to remote sensing and spatial data sets and algorithms used to estimate water use efficiency.

Training event 1

The first training event on Remote sensing and Hydrology was held from 2-5 April 2012 at the Stellenbosch University (SU). This training workshop was linked to the Honours course 716 on Spatial modelling presented at the Department of Geography and Environmental studies. Prof. Wim Bastiaanssen presented the course and was assisted by Caren Jarmain. A total of 28 people attended the training course – students and staff from SU, one person from the Western Cape Provincial Department of Agriculture and one person from Cape Nature (Figure 66). The training workshop included presentations on the theory and practical examples related to remote sensing and hydrology but with numerous practical exercises. Day 1 focused on introducing remote sensing and hydrology concepts, Day 2 on specific products including Rainfall, ET and Land use, Day 3 on Integrating various Data Sets for research and operational applications and Day 4 looked into using remote sensing data for Water Accounting. All the students registered for Honours course 716 had to complete an assignment on the final day, testing their understanding of the training material.

Details on the training course are provided in Jarmain (2012b).

Figure 66. Participants of the remote sensing and hydrology training courses presented in 2012 at Stellenbosch University (left) and in 2013 at the University of Pretoria (right)

Training event 2

A training course related to the spatial modelling of evapotranspiration and biomass production was presented from 25-28 March 2013 at the University of Pretoria (UP). Prof. Wim Bastiaanssen presented this hands-on training course which consisted of lectures and many practical examples. Each student had access to a computer with the ERDAS software and could perform the exercises.

The trainees consisted of a diverse group: students (mainly post-graduates from UP), consultants (Omnia, GWK and Santam) and lecturers at UP. On day 1 a total of 25 participants attended, but due to other commitments a number of participants did not attend the entire course (Figure 66).

The training course was challenging in the way that very few participants had any "spatial" data or programme use background, but Prof Bastiaanssen proved to be an excellent trainer, guiding participants step by step through the training exercises. Progression of the participants' skills and understanding from day one to day four was visible. Each participant was asked to provide feedback through a review form and the feedback received was generally very positive but some participants suggested that the course be presented over a longer period. Some course participants also indicated an interest in attending a similar training course but more focused on water resources management.

Details on the training course are provided in Jarmain *et al*. (2013).

6.4 CAPACITY BUILDING IN RESEARCHERS INVOLVED IN THIS PROJECT

The project involved researchers from different Universities – University of KwaZulu-Natal, TU Delft, Stellenbosch University, University of Pretoria, University of the Free State and the SA Sugarcane Research Institute (SASRI), having skills in various fields. This project exposed researchers to a range of data sets, technologies and models, whether through the training courses or just through their involvement in the project and working with the available data sets.

A few examples are given below:

- The SASRI team benefitted by gaining a better understanding of RS technology, its value and limitations and specifically how it can be used to improve (1) the agronomic efficiency of irrigated sugarcane production and (2) the quality of crop forecasts. Mr Francois Olivier, registered for his PhD on sugarcane water use and water use efficiency, further benefitted through his involvement in the project.
- Numerous UP staff members attended the remote sensing training course presented by Prof W Bastiaanssen and were exposed to the spatial data modelling.
- Staff and students from SU could collaborate with team members in related sciences and had access to spatial data sources.
- Staff from eLEAF was exposed to issues facing farmers in South Africa – how to manage water more efficiently and also to the needs of agricultural industries.

6.5 CAPACITY BUILDING IN FARMERS AND CROP INDUSTRIES INVOLVED IN THIS PROJECT

The technology partners, TSB and GWK, as well as farmers in the production areas were exposed to the spatial data sets through two web portals, SugarcaneLook and GrainLook and numerous meetings and discussions. The web portals were greatly used to transfer knowledge to a range of users on new, frequently available, spatially explicit data products related to growth and water, now available. The data available from these web portals formed the basis of discussions during many farmers and industry meetings listed below and were used extensively by TSB in farm evaluation and reporting. The conclusion is that, despite shortcomings with the web portals for data dissemination, or "data viewers" they served an important purpose of introducing different users to the data sets and also in determining requirements of future dissemination tools.

6.5.1 Technology transfer tools: Web portals

6.5.1.1 SugarcaneLook

The SugarcaneLook.co.za (alternatively www.sugarcanelook.com) data viewer (Figure 67) was designed by Apposition consulting and launched on 5 December 2011. SugarcaneLook was used to display and disseminate the data maps produced for the sugarcane study area. A link to the website was placed on the SASRI Crop resources website (www.sasa.org.za).

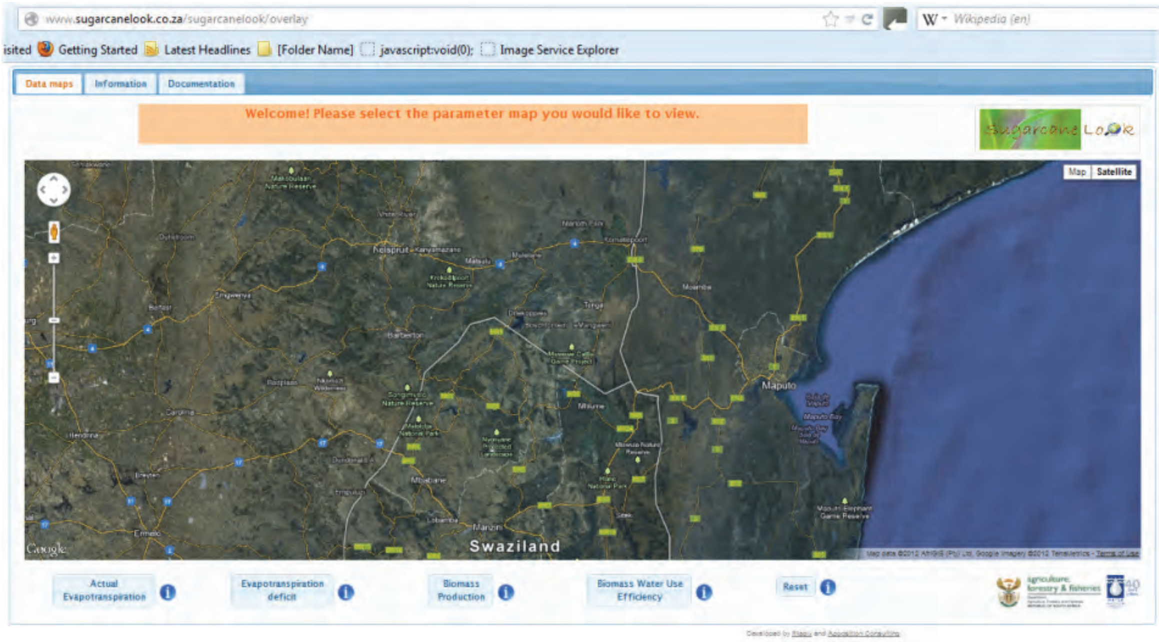


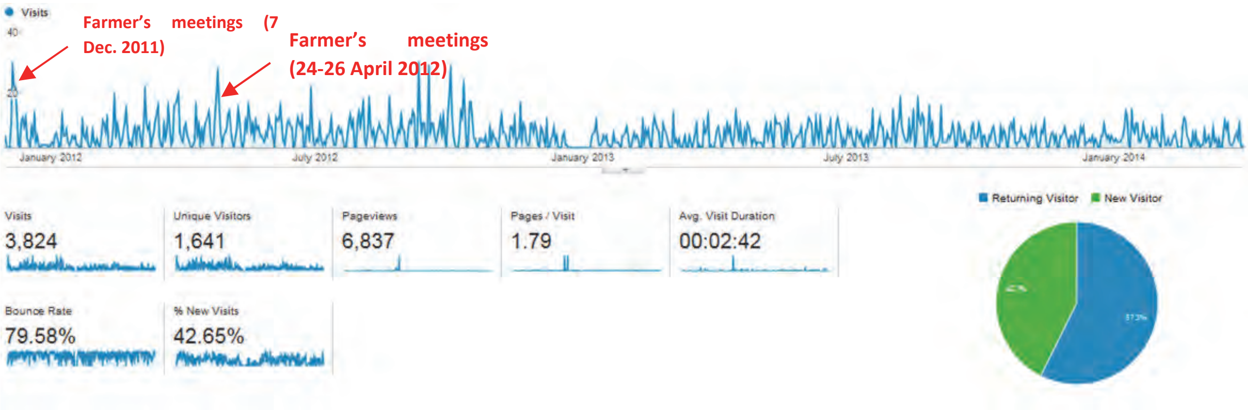
Figure 67. A Screen print of the SugarcaneLook website (www.sugarcanelook.co.za or www.sugarcanelook.com)

In the first few months of the project, many improvements were made to the spatial image processing to reduce the data processing time and hence the time it takes to make the data products from the website. It has been estimated that weekly SEBAL data maps of 30 m resolution for an area of 105 000 km^2 can be delivered within 2 days of receiving satellite imagery.

Data maps generated by the SEBAL modelling are in a format (GeoTIFF or raster) which cannot efficiently be displayed online due to its file size. Each SEBAL map therefore had to be converted into a picture (PNG) using a KML creator and these maps are displayed online together with a legend for data interpretation. The size of these converted picture files was substantially smaller and hence online data display faster. Missing data due to the presence of cloud cover was displayed in grey.

The Google analytics software tracked visits to the SugarcaneLook website, in an attempt to see if the website received visits and how often. Over the period 1 December 2011 to 31 August 2012 (Figure 68) a total of 1503 visits to the website occurred, with 48 % of these visits being return visits. The Google analytics showed that people not only from South Africa and the Netherlands visited the website, but also from United States (42), India (30), Colombia (24), Brazil (21), France (16), Australia (14) and the United Kingdom (13) amongst others.

There was an increase in website visits following the website launch (5 December 2011) and again following the farmer's meetings on e.g. 7 December 2011 and during the week of 24-26 April 2011 (Figure 68).



Country / Territory	Acquisition: Visits	Acquisition: % New Visits	Acquisition: New Visits	Behavior: Bounce Rate	Behavior: Pages / Visit	Behavior: Avg. Visit Duration
	3,824 % of Total: 100.00% (3,824)	42.65% Site Avg: 42.65% (0.00%)	1,631 % of Total: 100.00% (1,631)	79.58% Site Avg: 79.58% (0.00%)	1.79 Site Avg: 1.79 (0.00%)	00:02:42 Site Avg: 00:02:42 (0.00%)
1. South Africa	2,689 (70.32%)	34.81%	936 (57.39%)	77.43%	2.01	00:03:29
2. Netherlands	417 (10.90%)	39.33%	164 (10.06%)	83.21%	1.33	00:00:57
3. Pakistan	76 (1.99%)	14.47%	11 (0.67%)	92.11%	1.09	00:01:11
4. United States	70 (1.83%)	84.29%	59 (3.62%)	84.29%	1.23	00:00:53
5. India	56 (1.46%)	96.43%	54 (3.31%)	85.71%	1.20	00:00:21
6. Brazil	54 (1.41%)	74.07%	40 (2.45%)	77.78%	1.28	00:01:25
7. Colombia	49 (1.28%)	55.10%	27 (1.66%)	81.63%	1.24	00:01:03
8. (not set)	49 (1.28%)	69.39%	34 (2.08%)	79.59%	1.22	00:00:33
9. Australia	42 (1.10%)	85.71%	36 (2.21%)	83.33%	1.29	00:01:51
10. United Kingdom	30 (0.78%)	90.00%	27 (1.66%)	90.00%	1.13	00:00:35

Figure 68. Visits to the SugarcaneLook website over the period 1 December 2011 to 22 February 2012 as recorded with Google Analytics

6.5.1.2 GrainLook

Polymorph systems (previously Apposition consulting) designed the GrainLook data viewer which was used to disseminate data related to growth and water for an area around Douglas. Features of the planned viewer were enhanced for GrainLook as per request by GWK and farmers and included:

- Link to GrainLook on the GWK main website;
- Weekly data provision of evapotranspiration, ET deficit, biomass production and biomass water use efficiency for the period 1 October 2012 to 31 May 2013;
- Password protection – different users have access to the data using their own passwords;
- Farm location – upon login, farmers are redirected to their farm; and
- Logical legend – the ET deficit legend was changed in colour upon request by users so that red now represent a 'dry' or 'water stressed state' and blue the opposite.

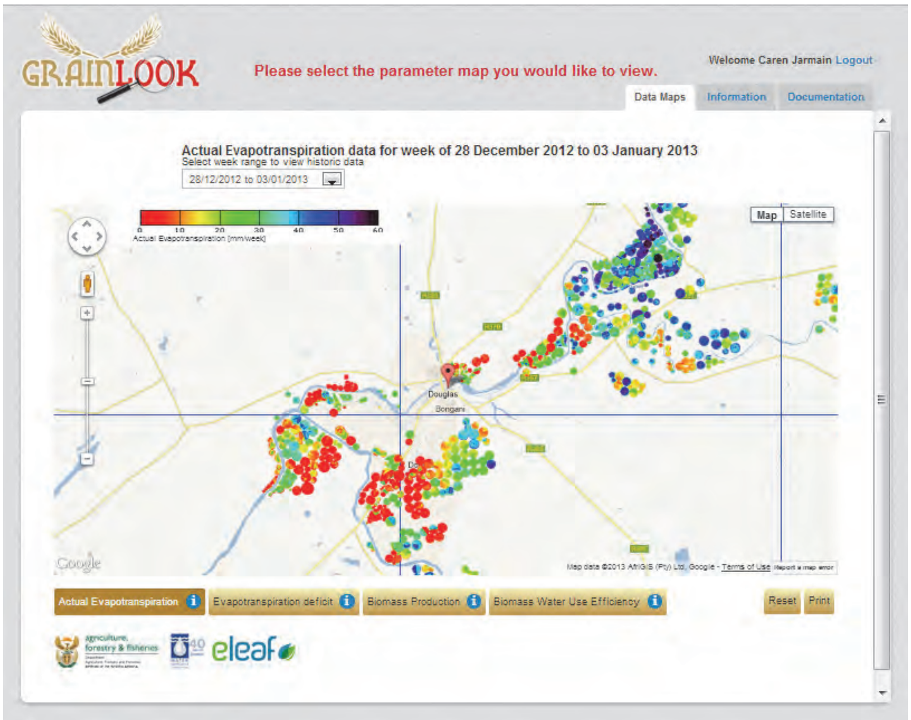
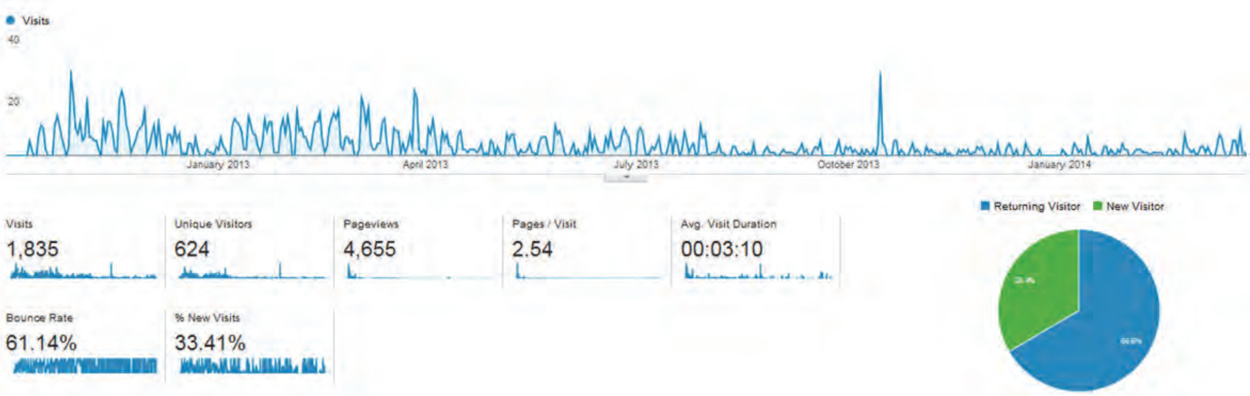


Figure 69. A screen print of the Grainlook.co.za website displaying actual evapotranspiration for the week of 28 December 2012 to 3 January 2013 for centre pivots around Douglas

For the spatial data displayed through the viewer to be used operationally, it is important that the data be delivered timely through the web portal. DMC satellite data was generally delivered within a day of acquisition which allowed the spatial data processing to be completed within 1.5 days and hence the new spatial maps could be delivered at weekly intervals. Since website speed is critical to maintain, the GrainLook data maps were compressed to a smaller size, but this resulted in a slight "blurred" look.

Google Analytics software was also used to track visits to the GrainLook website. Since the launch of the website early in October 2012, the website received 1818 visits (Figure 70). Of these 33 % was new visits, meaning 67 % was returning visit. The average amount of pages viewed per visit was 2.55. A number of farmers in the Douglas area were frequent visitors to the website.



Country / Territory	Acquisition: Visits	Acquisition: % New Visits	Acquisition: New Visits	Behavior: Bounce Rate	Behavior: Pages / Visit	Behavior: Avg. Visit Duration
	1,835 % of Total: 100.00% (1,835)	33.41% Site Avg: 33.41% (0.00%)	613 % of Total: 100.00% (613)	61.14% Site Avg: 61.14% (0.00%)	2.54 Site Avg: 2.54 (0.00%)	00:03:10 Site Avg: 00:03:10 (0.00%)
1. South Africa	1,501 (81.80%)	29.78%	447 (72.92%)	62.29%	2.69	00:03:22
2. Netherlands	148 (8.07%)	23.65%	35 (5.71%)	27.70%	2.47	00:02:48
3. (not set)	40 (2.18%)	62.50%	25 (4.08%)	60.00%	1.88	00:03:00
4. Mozambique	34 (1.85%)	2.94%	1 (0.16%)	70.59%	1.44	00:05:05
5. India	20 (1.09%)	100.00%	20 (3.26%)	95.00%	1.05	00:00:12
6. United States	18 (0.98%)	100.00%	18 (2.94%)	94.44%	1.11	00:00:24
7. United Kingdom	11 (0.60%)	90.91%	10 (1.63%)	100.00%	1.00	00:00:00
8. Colombia	4 (0.22%)	75.00%	3 (0.49%)	75.00%	1.75	00:00:15
9. France	4 (0.22%)	100.00%	4 (0.65%)	100.00%	1.00	00:00:00
10. Iran	4 (0.22%)	50.00%	2 (0.33%)	75.00%	1.25	00:01:16

Figure 70. Visits to the GrainLook website for the period 1 October 2012 to 31 May 2013 as recorded with Google Analytics

6.5.2 Farmers' meetings

6.5.2.1 Meetings on sugarcane

Numerous meetings were held with farmers from both Malelane and Komatipoort (Table 23) and farmers in the Douglas area (Table 24).

During the Malelane and Komatipoort meetings, the SugarcaneLook data was discussed in detail and many practical uses devised. In addition, the MyCaneSim® simulations with integrated soil moisture data provided valuable assessments on in-field irrigation strategies, which were improved over the study period.

Table 23. List of meetings held in the Malelane and Komatipoort area, to discuss data related to sugarcane water use efficiency

Date	Venue	Meeting focus	Attendees
19 July 2011	TSB, Malelane	Project launch meeting	TSB, Farmers, Project team, WRC
7 December 2011	Mpumalanga Cane Growers (Malelane) and TenBosch (Komatipoort)	Discussion of SugarcaneLook and MyCaneSim® data	TSB, Farmers, Project team
25 and 26 April 2012	Komatipoort and Malelane respectively	SugarcaneLook, MyCaneSim® and soil moisture data evaluation	TSB, Participating farmers, Project team
27 November 2012	Malelane Mill	Project evaluation meeting	TSB, Participating farmers, Project team
11 February 2014	Komatidraai, Komatipoort	General feedback and way forward	TSB, one farmer

6.5.2.1.1 MyCaneSim® Information transfer

The integrated MyCaneSim® system was demonstrated to, and results discussed with, commercial and small-scale farmers and extension specialists during a series of workshops held in Malelane and Komatipoort (25-26 April 2012 and 11 February 2014). Farmers received guidelines *via* e-mail on how to access and view the MyCaneSim® outputs (14 February 2012). At the meetings, each farmer was provided a booklet with instructions and set of simulation outputs (reports) for their respective fields, showing graphs of ASWC, rainfall and inferred irrigation, as well as expected yields (see Appendix VI) for an example).

Discussions with farmers and extension staff revealed that MyCaneSim®'s indication of waterlogging and drought stress was found insightful, as well as estimates of seasonal water requirement and final yield. Some farmers commented that yield estimates were close to what was achieved in reality, while all farmers were surprised that the system suggested that higher yields could be achieved. Another feature that users found useful was the predicted date of the next irrigation. Farmers suggested that future model simulations should take into account short and long term rainfall forecasts. One farmer commented that it would be useful to know when during the growing season the crop would benefit most from irrigation. Another important requirement was to know when to start irrigation after a rain event. MyCaneSim® provides information on both these aspects. The MyCaneSim® crop graph shows the part of the growing season during which stalks are growing (Appendix VI), which is when yield is most affected by lack of water (Robertson *et al.*, 1999). The start of irrigation after rain is provided in the irrigation advice report (Appendix VI) and can also be inferred from the soil water graph.

6.5.2.1.2 Meetings on maize

Similarly, the GrainLook data provided interesting discussion points for the Douglas farmers. Different crops and cultivars could be identified as well as irrigation application problems.

Table 24. List of meetings held in the Douglas area, to discuss data related to maize water use efficiency

Date	Venue	Meeting focus	Attendees
17 September 2012	GWK, Douglas	General meeting	GWK
17 October 2012	GWK, Douglas	General meeting	GWK
30 October 2012	GWK, Douglas	Project launch GrainLook data discussion	GWK, Farmers
12-13 February 2013	Meetings on individual farms	GrainLook data discussion	GWK, Farmers
14 February 2014	GWK, Douglas	GrainLook feedback	GWK
16 February 2014	GWK, Douglas	GrainLook evaluation meeting	GWK, Farmers, Project team

6.5.3 Sugar industry's use of spatial data

One of the project aims is "*Developing spatial WUE information generated with the SEBAL model to the point of operational use in South Africa*", hence pointing to the operational and commercial use of the spatial data products evaluated in this project. The use of the spatial data by the industry partner TSB was encouraging.

Dr Pieter Cronje from TSB extensively used the spatial data delivered through SugarcaneLook to prepare reports for different farms delivering to the TSB mills during 2011 and 2012. He used the SEBAL ET and biomass data to evaluate sugarcane farming practices (production and irrigation). In these reports, Dr Cronje combined data from an existing database used by TSB, CanePro, which captures production information from farms delivering to TSB mills, with the SEBAL spatial data. Where lower sugarcane production was recorded on the CanePro data base, he used the SEBAL ET data to explain the reduction in yield. He also used the SEBAL spatial data to look at differences in production by different cultivars and to compare crop water status between different but adjacent farms.

Dr Cronje illustrates through the use of the SEBAL ET and other data maps (biomass production, ET_{def} and biomass water use efficiency) that even the data displayed in "picture" format on a viewer like SugarcaneLook can be used by a commercial company to evaluate crop production changes. Some of these example reports can be viewed in Jarmain *et al*. (2013).

CHAPTER 7: KNOWLEDGE DISSEMINATION AND PUBLICATIONS

Communicating information on and results from the project with farmers, researchers and other stakeholders were an important part of this project. This was done through a popular articles published, presentations at conferences and scientific articles published. These are listed below.

7.1 POPULAR ARTICLES

An article on the project appeared in the September /October 2011 WaterWheel, "Improved water use only a satellite away". This followed the project launch meeting in Malelane in July 2011.

A news snippet on the project appeared in the January 2012 issue of 'The Link', a technical newsletter published by the South African Sugarcane Research Institute (SASRI) three times a year, "New technology to estimate irrigation water use and sugarcane biomass production". 'The Link' is available online at http://www.sasa.org.za/TheLink.aspx and also gets distributed free-of-charge to industry members.

Ms Lorna Hamman has also written a short article on this project for Spilpunt a magazine distributed amongst sugarcane farmers in Mpumalanga. The article was published in the May/June 2012 issue of Spilpunt, "Water projek vir Suikerriet". For the online version see http://www.spilpunt.co.za/issu/spilpunt_may_june_2012/index.html.

An article on SugarcaneLook was also published in April 2012 in the SA Sugar Journal entitled 'Water use efficiency initiatives in the Onderberg'.

7.2 PRESENTATIONS AT FORMAL MEETINGS AND CONFERENCES

7.2.1 South African Sugar Industry's Agronomist's Association's Symposium – Technology for Agronomy

Caren Jarmain was invited to present a talk at this meeting held on 25 October 2012 at Mt Edgecombe with the title 'SugarcaneLook Improving water use efficiency'.

7.2.2 SANCID2012

The SANCID 2012 Symposium with theme 'Irrigation in a Changing Environment' was held from 20 to 23 November 2012 at the Alpine Heath Resort in the Northern Drakensberg. The project team presented a number of talks related to this project.

Caren Jarmain presented a talk on Wednesday 21 November 2012 with the title 'Improving water use efficiency of irrigated sugarcane'.

Aresti Paraskevopoulos presented a talk on Wednesday 21 November 2012 with the title ' Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management'.

JARMAIN C, SINGELS A, OBANDO-BASTIDAS E, OLIVIER FO and PARASKEVOPOULOS A (2012). Improving water use efficiency of sugarcane. *Symposium of the South African National Committee on Irrigation and Drainage held from 20 to 23 November in Alpine Heath Resort, Drakensberg.*

PARASKEVOPOULOS A, SINGELS, A and VAN NIEKERK H (2012). Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. *Symposium of the South African National Committee on Irrigation and Drainage held from 20 to 23 November in Alpine Heath Resort, Drakensberg*.

7.2.3 Swaziland Sugar Conference

SINGELS, A, PARASKEVOPOULOS A and JARMAIN C (2013). Climate Change Impact on Productivity and Sustainability of irrigated Sugarcane Production: Exploring the use of Smarter Technologies for Improving Productivity and Water Use. S*waziland Sugar. Conference Held at Ezulwini, Swaziland on 17 September 2013 (Invited talk).*

7.2.4 SA GEO presentation

The second SA-GEO symposium will be held from 10-12 September 2013 at the University of Fort Hare. The focus of this symposium is "*Using Earth Observations for Informed Decision-Making in South Africa*". Caren Jarmain presented a talk entitled *"Moving beyond the intelligent pictures: From research to operations"*.

7.2.5 Australian Society of Sugarcane Technologists Conference

Dr Abraham Singels presented a paper at the Australian Society of Sugarcane Technologists Conference (www.assct.com.au) in May 2014.

SINGELS A, JARMAIN C, BASTIDAS-OBANDO E, OLIVIER FC, PARASKEVOPOULOS AL (2014). Validating water use and yield estimates derived from remote sensing and crop modelling for irrigated sugarcane in Mpumalanga, South Africa. *Proceedings of the Australian Society of Sugarcane Technologists 2014 Conference (In press).*

7.2.6 iLeaps 2014 conferences

Dr Caren Jarmain submitted an abstract for iLeaps 2014. However due to institutional delays, she could not attend this conference and the abstract submitted and approved had to be withdrawn.

JARMAIN C, BASTIDAS-OBANDO E, SINGELS A and STREVER A (2014). Sustainable Agricultural Production in South Africa: Examples of Spatial Data Use and Application Development. *Abstract submitted to the 4th iLEAPS Science conference, Terrestrial ecosystem, atmosphere, and people in the Earth System, 12-16 May 2014, Nanjing, China.*

7.2.7 Department of Plant Production and Soil Science (UP) Postgraduate Symposium

Two students presented at the Postgraduate symposium of Department of Plant production and Soil Science (UP):

TAVERNA-TURISAN D (2013). Assessing the accuracy of the SEBAL model to estimate crop evapotranspiration, biomass accumulation and nitrogen status. *University of Pretoria's Department of Plant Production and Soil Science Postgraduate Symposium, 29 August 2013.*

DLAMINI M (2013). Assessing the use of satellite imagery to estimate crop evapotranspiration and biomass accumulation using field measurements and modelling. *University of Pretoria's Department of Plant Production and Soil Science Postgraduate Symposium, 29 August 2013.*

7.3 SCIENTIFIC ARTICLES SUBMITTED

7.3.1 Journal of Computers and electronics in Agriculture

Mr Aresti Paraskevopoulos and Dr Abraham Singels has completed the first draft of an article they are planning to submit to the Journal "Computers and electronics in Agriculture" an Elsevier publication. The title of the publication is "Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management".

PARASKEVOPOULOS AL and SINGELS A (2014). Integrating weather based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. Computers and Electronics in Agriculture. *Computers and Electronics in Agriculture* (Impact Factor: 1.77). 01/2014; 105:44–53.

7.3.2 Journal of Field crop research

Mr Ernesto Bastidas-Obando submitted a publication "Canopy resistance behavior of rainfed and irrigated sugarcane described by leaf area index and environmental variables" to Journal of Field crop research as part of his PhD. The co-authors are Prof W Bastiaanssen and Dr C Jarmain.

7.3.3 Proc. S. Afr. Sug. Technol. Ass.

PARASKEVOPOULOS A and SINGELS A (2013). Integrating weather-based crop modelling and soil water monitoring technologies to provide improved decision support for sugarcane irrigation management. *Proc. S. Afr. Sug. Technol. Ass.* 86: 190-195

7.4 DRAFT SCIENTIFIC ARTICLES

A second publication related to this project and using a subset of this projects' data has been drafted by Caren Jarmain as part of the WatPLAN project. This publication will be submitted upon request to the Open Access Remote Sensing Journal for a special issue on "Hydrological Remote Sensing". The journal article has been circulated to some of the project team members and their comments are currently being integrated.

CHAPTER 8: APPLICATIONS AND CONCLUSIONS

8.1 INTRODUCTION

In this project various tools to assess water use efficiency of irrigated crops were investigated, within the context of an increasing international need to close the often large gap between the actual and attainable yield per unit of water consumption. In this section the results are placed in an international context and also within the context of the four project aims, which were to: (a) confirm the accuracy of SEBAL ET, biomass, yield production and WUE estimates; (b) illustrate how spatially explicit ET and yield data can be used to assess and improve the WUE for selected crops, (c) develop the SEBAL WUE information to the point of operational use in South Africa and (d) empowering students, researchers, extension officers, farmers with new technologies for improved WUE.

8.2 SEBAL DATA ACCURACY

Although this project focused on assessing the accuracy of estimates of evapotranspiration (ET), biomass, yield production and water use efficiency estimated with the Surface Energy Balance Algorithm for Land (SEBAL) model, it also presented the opportunity to assess the accuracy of estimates from field based crop growth models and specifically how they can be enhanced by incorporating timeously available spatial datasets (specifically for forecasting). The accuracy of the SEBAL estimates were assessed through comparison against other estimates (modeled and limited field measurements).

Since the formulation of SEBAL was first published in 1998 by Bastiaanssen, the accuracy of SEBAL evapotranspiration estimates have been evaluated in more than 30 countries (Li *et al.* 2009). Various spatial (field to catchment) and temporal (daily to seasonal) scales were considered, a range of climatic conditions and vegetation types and agricultural crops (dryland and irrigated). Typically, results have shown that SEBAL can estimate ET with accuracies of up to 85 % at a daily time step and 90 % over a season (Li *et al.* 2009).

Also in South Africa the accuracy of SEBAL has been evaluated in previous studies (Jarmain *et al*., 2009b; Jarmain and Klaasse, 2012; Dost *et al*., 2013; Kongo and Jewitt, 2006). Still, as also found by Karimi and Bastiaanssen (2014), the uncertainty of the possible errors in remote sensing estimates, remains a concern among users, also in South Africa. But, the challenge is in assessing and stating the accuracy of the ET products, often due to a general shortage of validation data (Karimi and Bastiaanssen, 2014). The general lack of validation data might be the reason for no publications found on the accuracy assessments of SEBAL biomass estimates or the satellite derived nitrogen estimates provided by eLEAF (formerly WaterWatch). In additions, there are also uncertainties related to the accuracy of field observed ET, as discussed by Li *et al*. (2009).

In the past, the accuracy of SEBAL data products has been assessed as part of research projects, where the processing of images were typically done all at once (Klaasse *et al*., 2008; Jarmain *et al*., 2009b; CSIR, 2012), but in recent years, the data accuracy has also been assessed in projects where SEBAL data was provided operationally, in near-real time (Dost *et al*., 2013; Jarmain and Klaasse, 2012; Strever *et al*., 2014). In the current project, the near-real time, operationally provided data was evaluated, which means there was less flexibility in the data selection and processing processes.

In this project, with the exception of a few data points, the SEBAL ET estimates typically exceeded the field observations, but the SEBAL estimates were similar to that from the crop growth models evaluated.

- SEBAL ET estimates for sugarcane agreed well with CaneSim® estimates, but exceeded the field observations, especially during the summer part of the growing season (slope=1.31, offset=2.63, R^2=0.781).
- SEBAL ET typically exceeded the observed maize ET, with the exception of three weeks in summer (slope=0.7919, offset=11.2, R^2=0.8074). SEBAL ET estimates exceeded the SWB estimates for periods of incomplete canopy cover.

The SEBAL biomass production estimates, corrected to C4 ADM, also agreed well with the observed estimates and typically exceeded the estimates from the crop growth models:

- SEBAL biomass estimates agreed well with the adjusted field ADM observations (slope=1.15, offset=1.1, R^2=0.89). This is an excellent result, considering that SEBAL TDM values are compared with measured ADM values and that TDM typically would be about 14% higher than ADM because of unaccounted root mass.
- For maize SEBAL ADM compared well with field observations, but with the final estimate slightly higher than that observed (slope=0.9938, offset=1311.8, R^2= 0.9333) and the SWB estimates (slope=0.9292, offset=827.13, R^2=0.9496).

The SEBAL yield models for sugarcane and maize both performed well. For sugarcane weekly yield increments were estimated from weekly ADM increments after the estimated start of stalk growth. For growth, weekly yield increments were estimated from weekly ADM increments after the start of maize flowering. Interesting to note though was that the SEBAL based estimates typically agreed better with final yield estimates at the mill (in the case of sugarcane) and the combine harvester data (in the case of maize).

- The SEBALMC (sugarcane) stalk dry mass estimates were marginally better than the CaneSim® estimates (80 *vs.* 82 % of observed variation explained), while both models tended to underestimate high values. Cane and sucrose yield at harvest was estimated poorly by all models.
- Forcing the CaneSim® Crop Forecasting System (CCFS) with SEBAL data improved the accuracy of yield and production forecasts for the 2011/12 season for the Komati mill. The April (leadtime of up to 9 months) forecasting error was reduced by 5.0 % by forcing the radiation version of CCFS with CC data, while the error was reduced by 7.1% when the ET version of the CCFS was forced with ET data.
- SEBAL maize grain yield estimates, based on accumulated ADM from flowering to harvest compared well with the spatial average yield from a combine harvester, with the exception of two fields showing large infield variations. SEBAL yield was typically lower than the SWB estimate and field observation, since the latter two yield estimates included the cob mass.
- Harvest indices derived from SEBAL ET and combine yield data showed values ranging from 0.39 to 0.57, with an average of 0.45 (0% grain moisture).

Estimates of WUE, using spatial data sets were always found to be lower than when only data from the crop growth models were used.

- Estimates of WUE for 11 sugarcane fields estimated with observed and estimated yield (SEBALTT) for 2012/13 were very similar (2.74±0.34 kg/m^3 and 2.70±0.46kg/m^3 respectively) and where only CaneSim® estimates were used (dry cane yield, ET) a lower WUE was found (2.55±0.25 kg/m^3).
- Estimates of WUE for 6 maize fields estimated using spatial data (SEBAL ET, combine yield) for the 2012/13 season was 1.51 ± 0.23 kg/m^3, higher than that for example estimated by Zwart and Bastiaanssen (2004) ranging from 1.1 to 2.7 kg/m^3.

Differences were found between the laboratory estimated nitrogen and spatial canopy nitrogen estimates. The differences are the result of the following (a) the laboratory analyses of N is based on samples from within a field, which could never be representative of an entire pixel or field, (b) N canopy percentage is the average N for the entire field, (c) the laboratory N estimates are estimated only for the youngest, fully developed leaves and (d) canopy N includes the nitrogen percentage of not only young, but also old leaves. Taking these factors into consideration, the nitrogen estimations can be evaluated more effectively in future studies. These spatial estimates of canopy N can likely be used in a strategic way over subsequent seasons to identify areas with N deficiency issues and relate this information with the dry biomass of leaves to assess the nitrogen canopy percentage.

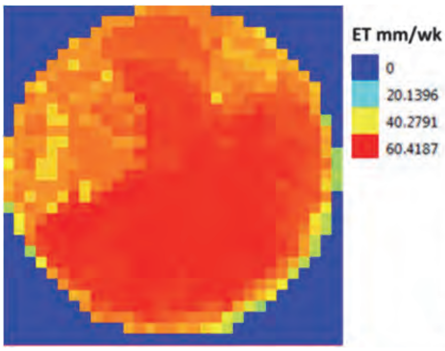
The validation results from this project are based on fairly small sample sizes and also accuracy assessments for SEBAL biomass and yield are not readily available from published literature to place the differences between the spatial and field observations in context. Nevertheless, Karimi and Bastiaanssen (2014) found a low absolute error for spatial ET products in general, 5.4 %, which was for example, substantially lower than the mean absolute error for rainfall estimates (18.5 %).

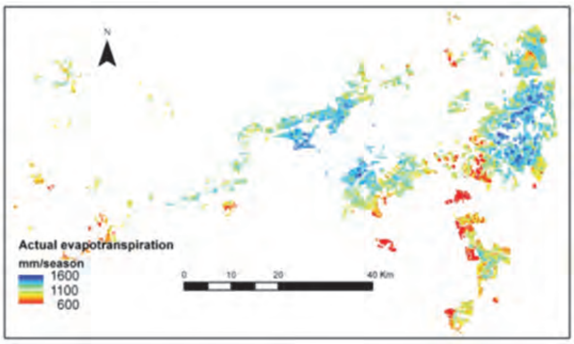
8.3 SEBAL DATA USES

The main benefits which a technology that uses satellite data and a physically based algorithm like SEBAL brings to agricultural and water management, is the fact that (a) data can be represented spatially and over time and (b) it is quantitative. Hence these spatial, and temporal quantitative data products can be used to evaluate farms and fields and to detect problems (anomalies) which can then be investigated further and addressed timeously. Farmers can subsequently be advised ito e.g. better water management, based on trends in the data over space and time.

8.3.1 Evapotranspiration and Evapotranspiration deficit

Whereas in the past a single ET value for example for a defined field or area were used / applied, now the variability within that area or field as depicted below, can be shown. Because of this, conditions can be assessed more accurately.





For example, typically a model like SAPWAT will estimate the water requirements of sugarcane produced in the Lowveld to be 1144 mm/yr and 669 mm/season for maize produced in the Northern Cape. Also, the fixed water allocation for sugarcane production in the Komatipoort and Malelane areas will be around 950 mm/yr and for the Douglas area about 1000-1100mm/yr (for dual cropping systems). The spatial SEBAL data however shows that a spatial variation in ET exists: for example for sugarcane production in the Malelane and Komatipoort areas, the average annual SEBAL ET estimate is 1092±252 mm/yr, hence a

23 % variation in ET exist around the mean. The SAPWAT ET estimates for example falls towards the higher end of sugarcane ET distribution.

Another example is for maize production in the Douglas region. GWK currently estimates the ET (from crop factors) to be typically around 715mm/season, depending on the exact planting date, whereas SAPWAT estimates ET as 623 mm/season. SEBAL ET estimates again show an average ET for maize for the 2012/13 season of 692±118 mm/season, or a 17 % variation in ET around the mean ET.

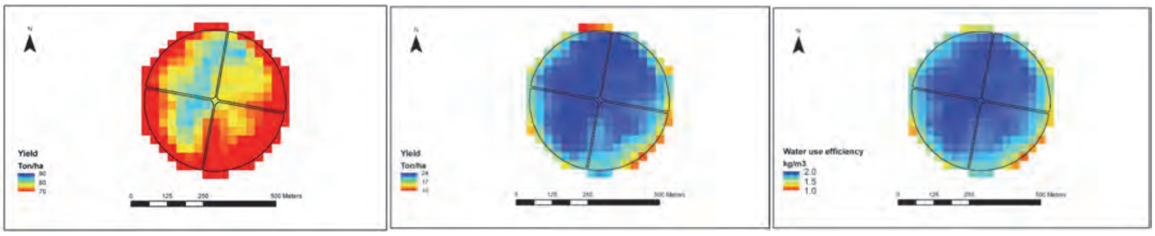
Although the ET from irrigated crops are mainly driven by atmospheric demand and the availability of radiation, water delivery through the system will probably be the main factor that will determine whether a farmer will get behind with its water applications or not, especially around periods with heat waves. But a better understanding of the spatial variability of ET across a region could greatly aid farmers and authorities in planning water distribution better.

Related to ET, the availability of ET_{def} data can also assist authorities and farmers in identifying areas more vulnerable to water shortages, which could be related more to system design. Frequent ET_{def} can indicated that farmers are falling behind with irrigation applications, but no ET_{def} over periods of weeks, together with low water use efficiencies could also indicated for example water logging.

8.3.2 Crop Yield and water use efficiency

Cane yield recorded at the Malelane and Komatipoort mills in 2011/12 and 2012/13 ranged between 69 and 142 t/ha for the fields monitored in this study. The optimal yields estimated with CaneSim® for these two areas and specific to the current irrigation system of these fields, range between 89 and 160 t/ha. Having an understanding of the differences between the actual and attainable yields can assist in reviewing the in-field irrigation practices and agronomic performance, as is described in Appendix III.

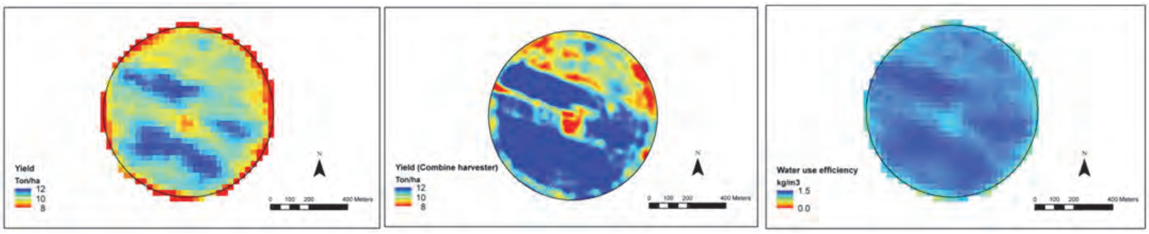
In addition, to using information from crop growth models like CaneSim®, to evaluate yield estimates for a specific field, an example is shown below depicting the spatial in-field variation in yield. For this field the mill recorded an average (low) cane yield of 88 t/ha, where the average yield estimated from the SEBAL data was 80 t/ha. The figure below clearly shows the large variation in yield within this pivot, ranging from 70 to 90 t/ha and stalk dry matter ranging from 10 to 24 t/ha. Investigating conditions in the areas of low production (orange to red colour) could provide answers as to the causes of the sub-optimal yield.



Evaluating yield data together with water use efficiency data for this field clearly shows that the areas with higher yields (cane and stalk dry matter) correspond with areas of higher WUE_{SDM} (1 to 2 kg/m^3). Some of the areas presented lower water use efficiencies which could indicate problems at field level on drainage or agricultural management. The only likely option to improve yields and water use efficiency for a field like this though, is likely to manage the irrigation water better.

Similarly for maize, with yields ranging between 8 and 10 t/ha (SEBAL estimate and combine harvester estimate), the water use efficiency was estimated to range between 1.0 to 1.5kg/m^3. For a field with a higher average yield (12 t/ha) an average WUE of 1.5 kg/m^3 was estimated. Some fields in the Douglas regions showed lower WUE, on average 1.0 kg/m^3, and reasons for this needs to be investigated but could be related to water management or the occurrence of pests or diseases. Optimal or attainable yield in the Douglas region is currently unknown, but probably exceeds the 14 t/ha currently achieved in this area. For example in the US Corn Belt, the average maize yield is typically around 13 t/ha (9.5 to 17.2 t/ha)

(Sandras *et al*., undated). In this high production area in the US, the WUE ranged between 0.82 and 1.94 kg/m^3 (average=1.4 kg/m^3). Zwart and Bastiaanssen (2004) estimated even higher WUE, ranging from 1.1 to 2.7 kg/m^3. Knowing and understanding the yield potential and yield range within an area and the associated water use efficiencies can help set benchmarks for crop production. The need to improve WUE may be clear to some producers or managers, whereas other may need to see specific incentives before addressing low yields and WUE's.



8.3.3 Crop forecasting

SEBAL data have the potential to enhance weather-based crop model applications such as yield forecasting. Currently crop model-based forecasts use historic weather records to represent the recent past and expected future to simulate yield for a limited number of cropping scenarios (e.g. Bezuidenhout and Singels, 2007). Hence, forecasts have to rely on broad assumptions with regards to average soil and crop properties and irrigation practices for each scenario. SEBAL data could be used to (1) reset the current state of the crop (canopy cover, crop water relations, growth vigour, ADM) in model simulations, and (2) introduce a finer resolution to yield forecasts, effectively increasing the number of scenarios, and spatial variation, covered. This project has shown beyond any doubt that the quality of yield and production forecasts can be improved markedly by using SEBAL data as input into the CaneSim® Crop Forecasting System.

8.3.4 Nitrogen

Since nitrogen varies spatially and over time, satellite derived canopy N estimates can possibly be used in a strategic way in future, over subsequent seasons, to identify areas within a field with N deficiencies and then relate this information with the dry biomass of leaves to assess the nitrogen canopy percentage. In the Douglas region, with numerous N applications over the maize growing season, frequent canopy N information with a spatial dimension will allow the farmer to respond to nitrogen shortages before tasseling and during grain filling.

8.3.5 Sugarcane industry data uses

Dr Pieter Cronje from TSB, shared reports prepared by him for different farms delivering to the TSB mills, in which he used SEBAL ET and biomass data to evaluate the sugarcane farming practices (production and irrigation). In his reports, Dr Cronje combines data from an existing database used by TSB, CanePro, which captures production information from farms delivering to TSB mills, with the SEBAL spatial data. Where lower sugarcane production was recorded on the CanePro data base, he used the SEBAL ET data to explain this. He also used the SEBAL spatial data to look at differences in production by different cultivars and to compare crop water status between different but adjacent farms.

See as an example of the report generated for the farm Libuyile in Appendix VII.

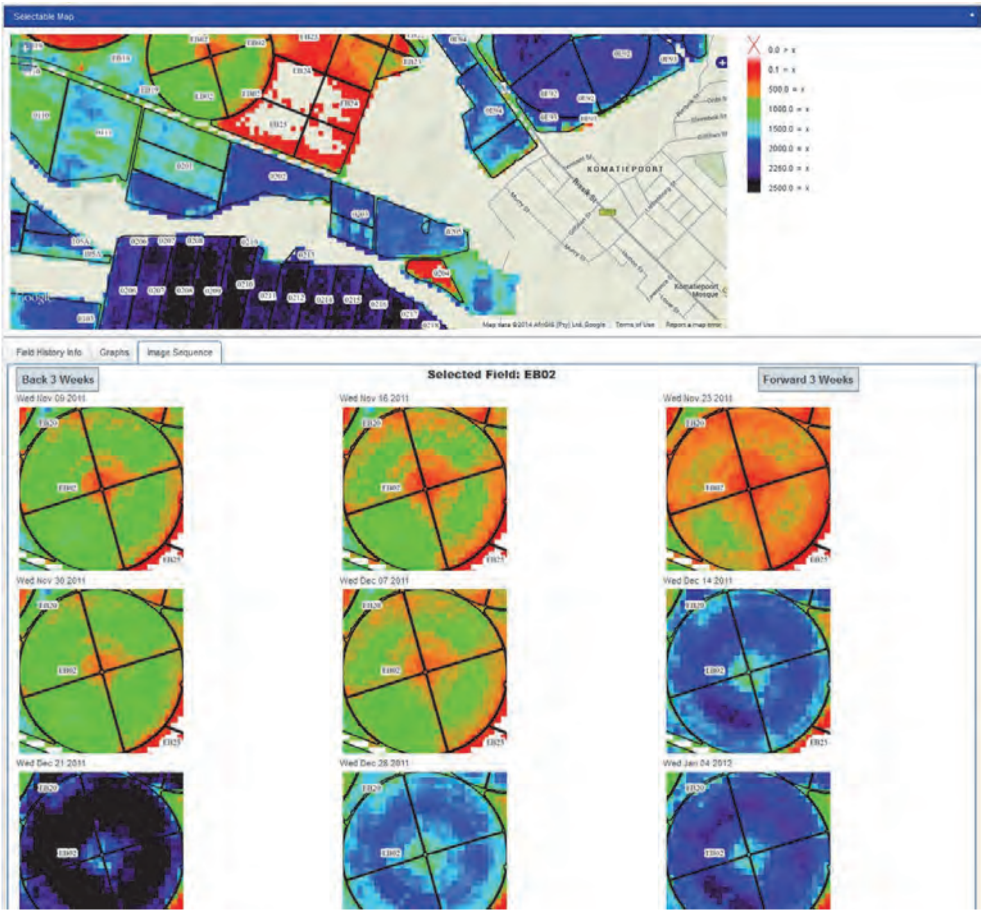
Dr Cronje illustrates through the use of the SEBAL ET and other data maps (biomass production, ET_{def} and biomass water use efficiency) that even the data displayed in "picture" format on a viewer like SugarcaneLook can be used by a commercial company to evaluate crop production changes.

8.3.6 *Developing SEBAL data to the point of operational use using graphical interfaces*

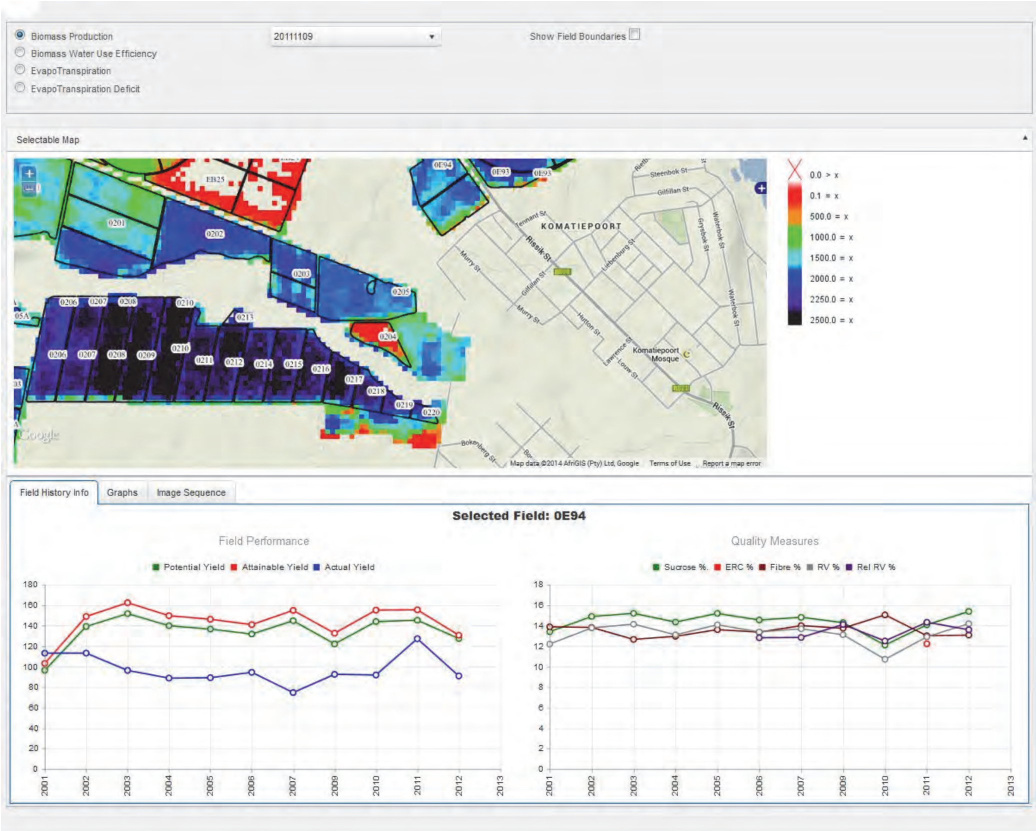
SEBAL data were shown as weekly images on a Web viewer (www.SugarcaneLook.com viewable in Google Chrome) with pixel values represented by a range of colours. Although these images were deemed useful, it is difficult for users to summarize data for a season, as a basis for investigating problems on fields and recommending corrective actions. On the current web viewer the images were slow to load due to the size of the data sets and data *per se* were not given, but had to be roughly inferred from a colour legend. It will be more useful to provide "business intelligence" – i.e. the underlying data is interrogated to produce both summaries of to-date, and predicted values at harvest of ET, biomass and cane yield, and compare these to potential benchmarks.

Together with two companies (SQRsoftware and Enterprise Evolution) that already provide information services to sugar industries, the development of an improved data query and reporting module to produce useful information for supporting crop and water management were explored. A preliminary version created by SQRsoftware has the following functionality (see also screen prints below):

- Depicting heterogeneity between and within the fields on crop production and water consumption at 30m resolution but also simplifying the heterogeneity into fewer classes of variation,
- Extracting to-date ET, ET deficit, biomass and cane yield, and water use efficiency at a field level and benchmark these against potential or optimal values,
- Extract predicted values at harvest of biomass and cane yield at a field level,
- Generating and displaying the data sets in time series graphs of variables up to the current date, as well as for remaining part of the growing season, and
- Presenting information in downloadable and printable tables, reports and images.



Selectable Map
KOMATIEPOORT
0.0 > x
0.1 = x
500.0 = x
1000.0 = x
1500.0 = x
2000.0 = x
2250.0 = x
2500.0 = x
Field History Info
Graphs
Image Sequence
Back 3 Weeks
Selected Field: EB02
Forward 3 Weeks
Wed Nov 09 2011
Wed Nov 16 2011
Wed Nov 23 2011
Wed Nov 30 2011
Wed Dec 07 2011
Wed Dec 14 2011
Wed Dec 21 2011
Wed Dec 28 2011
Wed Jan 04 2012


Biomass Production
Biomass Water Use Efficiency
EvapoTranspiration
EvapoTranspiration Deficit
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Show Field Boundaries
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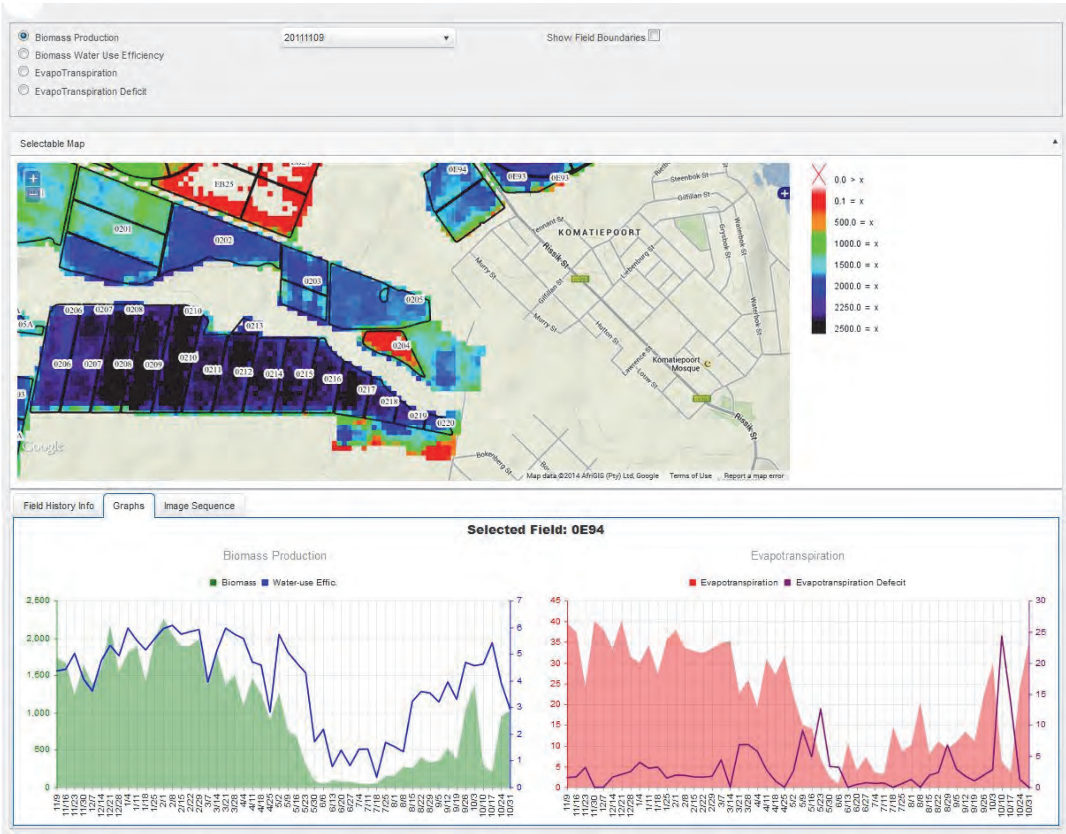
Quality Measures
Sucrose %
ERC %
Fibre %
RV %
Rel RV %


Biomass Production
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Evapotranspiration Defecit

The functionality was demonstrated as part of the CanePro package during a workshop with the project team and prospective users. There was general agreement that the tool will promote improved efficiency of water use for irrigation, resulting in more tons of sugar produced per unit of irrigation water applied. It will also allow growers, extension and water user association staff to identify poorly performing fields early, and focus remedial actions on these. The current project has created awareness and curiosity and it is believed that adoption would be rapid, provided sustainable funding for SEBAL data can be found.

8.4 CAPACITY BUILDING AND DATA OPERATIONALISATION

This project used the data viewers, SugarcaneLook and GrainLook, to expose different users (producers to managers) to spatial ET and growth related products. These viewers disseminated data at a weekly timestep and through consultation with users throughout the project, the different agricultural users were encouraged to consider "industry" related uses of the spatial data products. Users were further encouraged to observe the data and assess the accuracy in terms of what it could (and could not) detect first hand, hence doing a qualitative assessment of the data.

The sugarcane users have generally accepted the accuracy of the SEBAL data and specifically Dr Pieter Cronje (TSB) has used the data extensively over the past two years in his reporting, specifically to evaluate the performance of specific fields and farms. He integrated (manually) the SugarcaneLook data, with field knowledge as well as data captured through the CanePro data base.

In addition and through evaluation of the data products (ET, ET_{def}, Biomass, WUE and later Yield) it became clear that for the sugarcane industry the data products hold great value, specifically ito improving yield forecasting (at mill level). But also in evaluating and advising on on-farm production practices. Because of the extent of the production area, the users will not only require the detailed spatial data sets, but simplified data sets per field or a delineated area. Discussions with SQRsoftware, developers of CanePro have taken place, and a prototype proposed, which would integrate the current SEBAL data products into the CanePro system, with additional viewers developed. The value of this approach is the SEBAL data sets can be linked to existing sugarcane databasis within CanePro, adding more value to an existing platform currently being used.

Operational uses have also been illustrated to GWK and the maize producers in the Douglas area, but the focus here is not so much on yield estimation, but rather on water management, specifically using the ET and ET_{def} data sets. GWK could in future use the spatial data to improve the irrigation advice provided per individual field. Currently these users are not fully convinced of the accuracy of the data and the current cost of implementing such a service in the area currently makes this an unattractive option.

8.4.1 Limitations to operationalisation of spatial data

Both TSB and GWK have indicated that the data provided through this project, through the SugarcaneLook and GrainLook viewers holds great potential value to their industries. The fact that the spatial variation in fields can be displayed continuously (weekly), over the season, holds immense value. The commercial value lies in the fact that areas where crop growth was not optimal can be identified: problem areas can be investigated in time to do recommendations before crop losses occur under most instances. Also, the use of spatial images to determine nitrogen deficiencies will also be of great use.

However, for the adoption of this technology into these industries, a number of limitations and challenges will have to be addressed.

- *Longer term exposure to new data product*: Assessing the data products over a longer period will be very beneficial to industries. The period for which data was available through this project (18 months for sugarcane and 9 months for maize) was just too short. Longer term exposure to this relatively new technology will allow farmers and advisors to get more familiar with the technology, data to be evaluated over more than one season and also for a variety of crops. For example, in South Africa, spatial data through the FruitLook project has been available to farmers now for 4 consecutive seasons and the longer term technology exposure is bearing fruit ito involvement of users and their understanding of the data uses.

- *Data translation and integration*: To add value to the spatial data maps and to translate the data into concrete advice, agronomists with a good understanding of the area and crops are needed. Integrating the spatial data into existing datasets (soil moisture, etc.) could prove very beneficial. For example, a number of consultants in the Western Cape have adopted the FruitLook data as an integral part of the commercial service to producers. The FruitLook data is used in addition to field data. But, in general unfortunately there is currently a big human capacity need: especially for crop specialists with spatial or remote sensing skills or understanding and this is hampering the data translation and adoption possibilities in South Africa. Related to that, there is a great need for the spatial data to be integrated with other data sets and models to allow for predictive capabilities (irrigation scheduling, crop production estimation and forecasting, etc.).

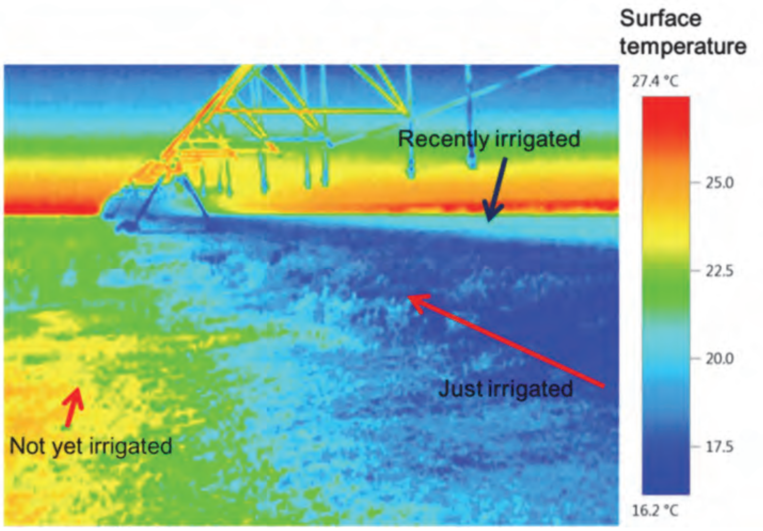
- *Data costs*: Currently the cost of the imagery (DMC) required for high resolution, frequent updates of this type of spatial data, is too high to be adopted quickly; unless overwhelming benefits can be illustrated – ito electricity, fertilizer use. Initiatives through the Department of Science and Technology and SANSA to obtain high resolution satellite data for South Africa that can be used in generating the growth and water use related spatial maps, will greatly facilitate adoption by crop industries.

8.5 DATA LIMITATIONS

All data sets, whether derived from satellite information, observed in the field or estimated using field scale models, have limitations.

Where satellite data is used in spatial modelling, a number of technological limitations are imposed. Li *et al*. (2009) list a number, including problems related to the remote sensing data itself as well as uncertainties in the accuracy of the retrieved land surface variables, uncertainty of the remote sensing ET algorithms, shortage of estimates of near surface meteorological data, spatial and temporal scaling effects, shortage of ET data at satellite pixel level for the validation purposes. Below a number of these aspects are discussed in a bit more detail.

- Data resolution: Data resolution includes the temporal, spatial and spectral resolution as defined by the sensor characteristics. For example, DMC only captures data in the visual (green, red) and near-infrared spectral ranges, but not in the thermal-infra range and cannot be used solely in SEBAL for ET estimation. The DMC data has to be combined with another sensors thermal data (MODIS, VIIRS, Landsat-8). Also, often data is available at a high temporal resolution (daily, e.g. MODIS), but at a low spatial resolution (1km). For certain applications this will be of great use, but for agricultural management frequent data updates are required – at least at weekly time interval. The data of image capture and conditions in the field (e.g. surface temperature before or after irrigation application) becomes important in interpreting data, as the picture below shows. Here the surface temperature differences are clear from areas in a pivot recently irrigated, just being irrigated and not yet irrigated. Similar types of information (land surface temperature) are used in the SEBAL modelling.



- Cloud cover: The presence of cloud cover remains problematic, since satellites sense the temperature of the cloud and not the surface temperature. In the sugarcane component of this project, cloud presence and the lack of suitable satellite images posed a bigger problem than in the maize component. Increased image capture frequency or availability of images from more satellites could assist in overcoming this problem, but this may currently be unrealistic ito of cost. Rather, new methods like the ETTool (Bastiaanssen *et al*., 2012) which attempts to overcome this problem by inferring actual evaporation and transpiration from a combination of optical and passive microwave sensor data, sensors which can observe land surfaces even under persistent cloudy conditions, should be further investigated. In addition, there is currently a great interest in in the use of drones in capturing relevant spatial information that can be used to assess crop performance. However, many challenges still exist in using this effectively, especially over extensive area. At the moment the spatial information derived from these platforms are currently mainly qualitatively and not quantitatively like the SEBAL or ETTool data.
- Lack of knowledge of field conditions: The lack of knowledge on field conditions (e.g. crop type, occurrence of crop lodging, chemical ripener application, outbreak of diseases, etc.) can provide an obstacle in interpreting the spatial results effectively and hence for operational application of the data, linking a data base with captured field conditions to the spatial data, could prove invaluable.

Also, weather and soil based crop models which are typically applied only to a point in the field have their limitations. This relates mainly to how well the field (climate, plant, soils) conditions represent the entire field and whether the point based results are relevant for an entire field. This project showed that often within a field, large variations were visible. Also, the use of actual weather data or longterm climatic data in the simulations, will affect the value of the simulations in real or near-real time.

Similarly, field observations have their limitations and again the question is posed as to the relevance of field observations to an entire field. For example, in this project it was shown that the field observed yield estimates (though based on a number of repetitions), often differed from that observed at harvest, whether by the mill or the combine harvester and this shows that often in field observations, the effected of the in-field spatial variation is not captured.

8.6 PROJECT CONCLUSIONS

It can be concluded that this project was successful in confirming that the degree of accuracy of data products from the Surface Energy Balance Algorithm for Land (SEBAL) model is acceptable for application South Africa.

The accuracy of the SEBAL data products, ET, ET_{def}, CC, Biomass and biomass water use efficiency, was tested extensively:

1. for two important agricultural crops: sugarcane and maize,
2. in 20 fields: representing a range of climatic, soils and agronomic conditions,
3. over a period of 26 months: 18 months in sugarcane and 8 months in maize, and
4. against field observation and accepted South African crop growth and water balance models: CaneSim®, SWB, SAPWAT.

The integration of data products (point based and spatial) with field scale models are beneficial for improved modelling (estimations or forecasting) and creates the potential of new data products to be derived. For example, reliable yield information would be more useful to potential users than SEBAL biomass data alone.

The SEBAL data products were further developed for yield estimation and yield forecasting. It can be concluded that these yield estimates and the forecasted cane yield is an improvement on the current method used. Also, that yield estimates and forecasting can be further improved with frequent and consistent updates of the SEBAL data, i.e. data with no gaps or infilling required.

The SEBAL yield estimates can be improved for maize with the identification of the exact point of flowering. And also, the integration of SEBAL data sets into a crop forecasting system for maize can prove to be very beneficial.

The integration of field data (soil water content) into the web-based MyCaneSim® system, often used in decision support for operational irrigation management, improved forecasting of yields at field level when weather-based simulations are reset with soil water records.

It can be concluded that this project was successful in showing how spatially explicit data from SEBAL model can be used by different users and for selected irrigated crops.

The SEBAL data provided through this project is quantitative and has a spatial dimension. It can be provided over an extensive area e.g. the entire Lowveld sugarcane production area, but with detail at a 30m spatial resolution. This brings many uses.

General farming practices can be evaluated ito ET, ET_{def} and water use efficiency and recommendations derived, as was done by Dr Cronje (TSB). Problems can be identified early and addressed.

For example, water management over an extensive area can be evaluated and proved, but similarly on a field or farm level since the required detail exist.

Estimates of biomass productions provides substantially more value than pure NDVI estimates in term of assess growth and crop production.

The ET_{def} data can be used effectively to define periods when improved water management is required, whether indicated drought or waterlogging. Similarly, poor water management can be identified by the water use efficiency (biomass or yield related). Deriving benchmarking values could prove invaluable for identifying problem areas.

Recommendations do not have to be based on a single value anymore (e.g. irrigation requirements of a crop), but can be derived from spatial data showing the area variation.

With the use of the spatial SEBAL data, crop forecasting can be improved at mill level.

The impact of diseases or water stress on biomass production and crop yield can be evaluated.

It can be concluded that this project was successful in developing the SEBAL data products to the point of operational use in South Africa.

The spatial SEBAL data has been further developed through this project, to the point of operational application.

For sugarcane:

The focus for operational application of the SEBAL spatial data has been on both yield estimation and forecasting and farming practice evaluation. The CaneSim® Crop forecasting system of SASRI has been developed to the point where SEBAL data, if available, can be used to improve yield forecasts at mill level. Further, the propotype data viewer developed by SQR software, integrating the SEBAL data into the CanePro data base, can effectively be used operationally to make evaluation of farming practices (irrigation, etc.) over different temporal and spatial scale more effective.

The fact that SEBAL data was available to the sugarcane industry to 18 months, greatly aided in the developed of the data to this point.

For maize:

For the SEBAL data to be operationally used for maize production, further exposure to the data and technology is required and hence further product development. The period of data exposure (8 months of data over a 12 month period) was too short. However, GWK is very open to the future of the SEBAL data, but specific products related to water, crop and nutrient management will have to be developed. E.g. a data viewer similar to that developed by SQRsoftware for viewing and evaluating farming practices, which can be integrated with the current GWK data base. There is also a need to derive benchmarking values from the SEBAL data, to make the application of data for irrigation scheduling and nitrogen management easier. A need further exists for integrating the SEBAL data into a model for crop forecasting.

We conclude that technology adoption and the operational use of data takes time and that in this project this was mainly achieved in the sugarcane sector.

This project was successful in building capacity in the use of spatial and field based technologies, from researchers, students, farmers and industries.

Researchers:

This project allowed for general exposure of researchers to remote sensing SEBAL data products but also first-hand evaluation of the data and its accuracy.

The integration of the spatial SEBAL data into a simplified version of the CaneSim® model for yield estimation and into the existing model for Cane crop forecasting, proved that the accuracy and value of the spatial data was recognized by researchers and that the integration process improved the yield estimates and forecasts.

Researchers from institutions like South African Sugarcane Research Institute, University of Pretoria, Stellenbosch University, University of KwaZulu-Natal and the University of the Free State were exposed to the new technologies.

Students:

Four training courses were held, two in-field and two remote sensing application focused, which exposed a total of about 80 final year and post-graduate students.

The project also produced an opportunity for students to engage in post graduate studies related to this project. This includes: 2 PhD, 3 MSc, 3 BSc Hons and one BSc student.

This project exposed students from five universities and two research institutes to the new technologies: South African Sugarcane Research Institute, University of Pretoria, Stellenbosch University, University of KwaZulu-Natal, the University of the Free State, CSIR and the University of the Western Cape

Farmers:

Farmers producing sugarcane and maize within the study areas were exposed to the latest spatial technologies. Access to the data through the web-portals SugarcaneLook and GrainLook as well as meetings to discuss the data from individual fields and farms, facilitated this technology transfer and building of capacity in the use of this data. Over the three years tens of farmers were exposed in both study areas.

Industries:

Technology transfer to our two industry partners in the project (TSB and GWK) was successful. This was illustrated in for example the active use of the SEBAL data disseminated through the SugarcaneLook webportal in farm evaluations and reports produced by Dr Cronje from TSB. The use of the data here showed a clear understanding of the use of the data and also the vision of integrating the data into existing platforms (CanePro) for future use.

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APPENDICES

APPENDIX I: VALIDATION OF FIELD ESTIMATES OF THE COMPONENTS OF THE ENERGY BALANCE AND DAILY ET OF SUGARCANE

VALIDATION OF FIELD ESTIMATES OF THE COMPONENTS OF THE ENERGY BALANCE AND DAILY ET OF SUGARCANE

Instantaneous energy balance data comparison

Net radiation (R_n) measured and estimated with SEBAL at the sugarcane show a decrease in the values from January to May 2012 (Figure AI.1). A good agreement existed between the measured and SEBAL data (with the exception of the first two data points), with SEBAL significantly explaining 86 % of the variation in the measured R_n ($p<0.05$; $R^2=0.86$) (Table AI.1). The soil heat flux density (G) measured and estimated showed differences, but also agreements on certain dates (Figure AI.1).

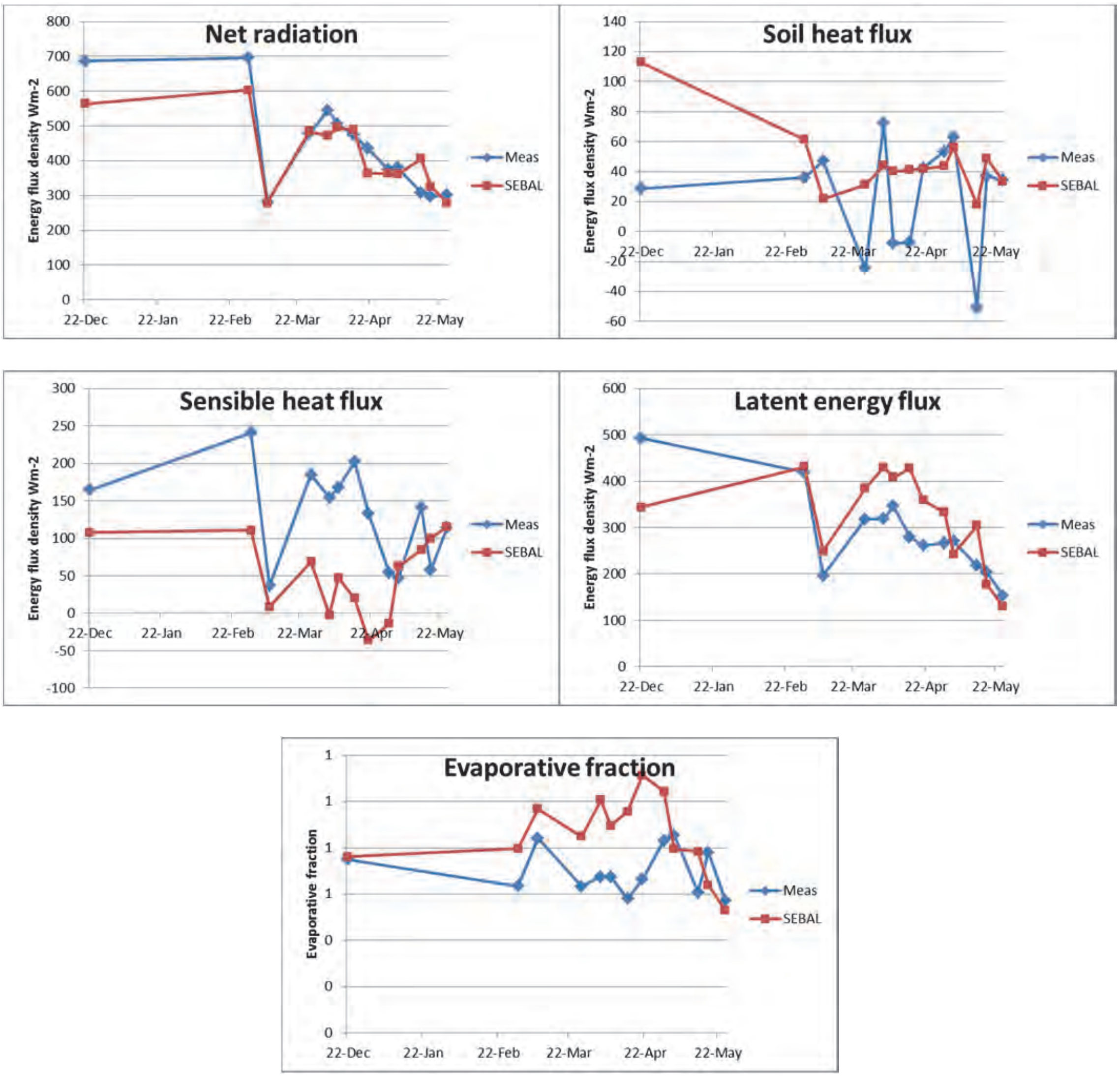


Figure AI.1. Comparisons of instantaneous estimates of net radiation (R_n), soil heat flux (G), sensible heat flux density, latent energy flux density (LE) and evaporative fraction (EF) with SEBAL with measured data at the sugarcane site

Table AI.1. Regression statistics (measured *vs.* SEBAL) estimated for energy balance parameters estimated at the time of satellite overpass and for that day and also for daily ET at the irrigated sugarcane site

Measured *vs.* SEBAL : Maize										
Regression stats	Instantaneous					Day				
	Rn_i	G_i	H_i	EF_i	LE_i	Rn_24	G_24	H_24	LE_24	ET
Multiple R	0.93	0.31	0.23	0.18	0.67	0.97	0.62	0.90	0.81	0.86
R Square	0.86	0.09	0.05	0.03	0.45	0.95	0.38	0.81	0.66	0.74
Adjusted R Square	0.85	0.01	-0.03	-0.06	0.40	0.94	0.32	0.79	0.63	0.72
Standard Error	40.21	23.39	52.82	0.17	76.98	10.81	1.35	23.03	25.41	0.84
Observations	13	13	13	13	13	13	13	13	13	13
Significance F (p)	4.38E-06	3.07E-01	4.49E-01	5.53E-01	1.23E-02	2.42E-08	2.46E-02	3.20E-05	7.36E-04	1.57E-04
Intercept	114.66	40.79	27.63	0.65	119.80	12.88	1.09	-96.23	18.10	0.24
X Variable 1	0.69	0.20	0.18	0.30	0.71	0.95	-0.11	1.32	0.57	1.28

The sensible heat flux (H) measured almost consistently exceeded that estimated with SEBAL. The underestimation in the SEBAL H estimates was substantial (Table AI.1). The latent energy flux estimates (LE) agreed better than H estimates, with the SEBAL estimates explaining 45 % of the variation in the measured LE at the sugarcane field (R^2=0.45)($p<0.05$) (Table AI.1). The SEBAL latent energy flux estimates almost consistently exceeded that measured (Figure AI.1). The evaporative fraction data showed similar trends (Figure AI.1).

Daily energy balance data comparison

The daily SEBAL estimates of the energy balance were compared to that observed at the sugarcane field for the days that satellite data was available for. Data comparisons show similar trends to that found for the instantaneous data. Net radiation estimates measured and modeled were very similar (Figure AI.2). The SEBAL estimates explained 95 % of the variation in the daily average measured R_n (R^2=0.95) (Table AI.1). The Sensible heat flux density showed larger differences (Figure AI.2), with the SEBAL estimates consistently being lower than that observed. The SEBAL estimates explained 81 % of the variation in the daily average measured H (R^2=0.81) (Table AI.1). The measured and the SEBAL estimates of LE showed an agreement in the daily estimates (Table AI.1, Figure AI.2), with the SEBAL estimates consistently being lower than that observed (R^2=0.81, slope=0.57).

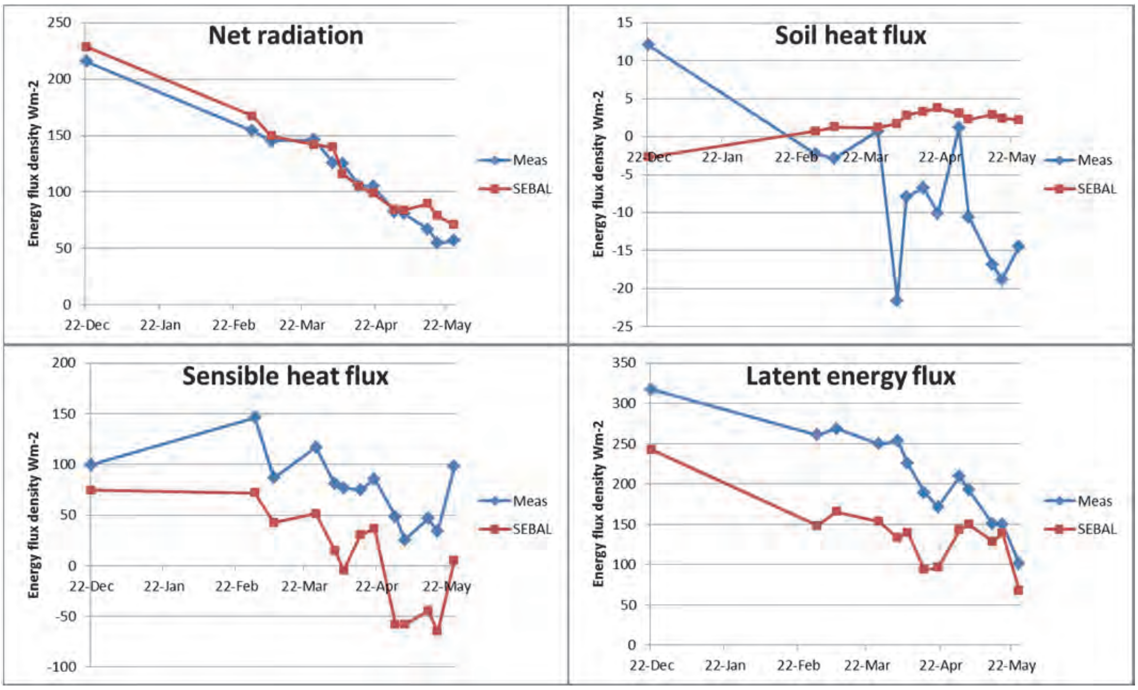


Figure AI.2. Comparisons of daily estimates of net radiation (R_n), sensible heat flux density, latent energy flux density (LE) and evaporative fraction (EF) with SEBAL with measured data from the sugarcane field

Daily evapotranspiration comparison

The daily SEBAL ET estimates were compared to the observed (measured) ET. The daily ET estimates with SEBAL consistently exceeded that observed ET (Figure AI.3). The linear regression showed that the SEBAL ET estimates explained 74 % of the variation in the measured ET (R^2=0.74) (Table A1.1). The slope of the linear regressions for the maize field was 1.28 (Table A1.1).

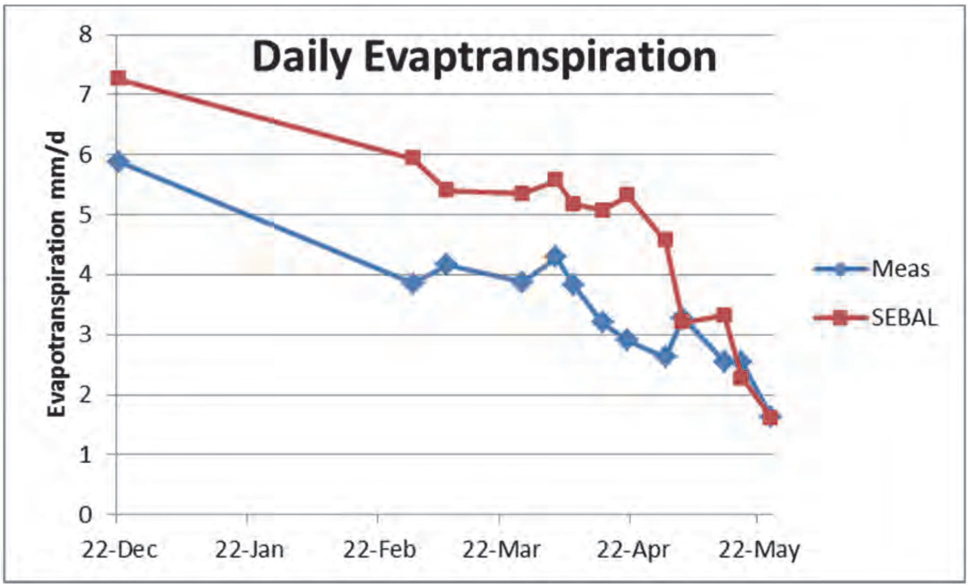


Figure AI.3. Daily evapotranspiration observed and estimated with SEBAL at the sugarcane field

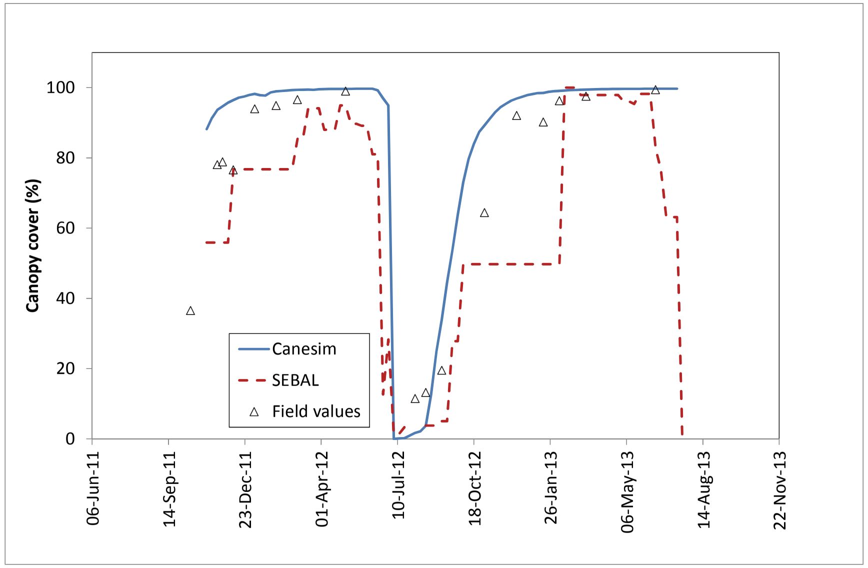
APPENDIX II: ADDITIONAL COMPARATIVE DATA FROM SUGARCANE FIELDS STUDIED

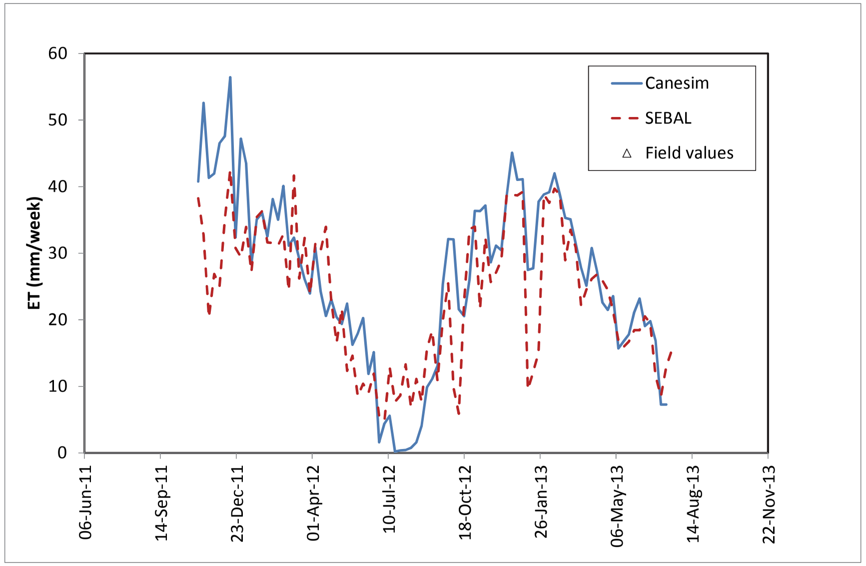
ADDITIONAL VALIDATION DATA FROM SUGARCANE FIELDS STUDIED

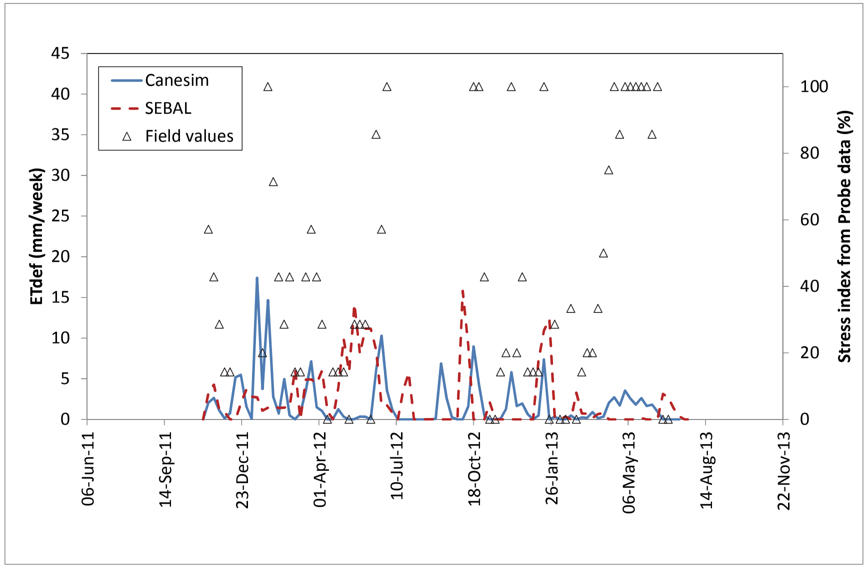
Two data sets are shown below, for each sugarcane field studied. First, the time series of simulated (SEBAL, CaneSim®) and observed canopy cover (CC), evapotranspiration (ET), evapotranspiration deficit (ET_{def}) and biomass for each field and for both seasons are shown. Secondly, the time series of fresh and dry stalk mass, stalk sucrose mass and sucrose content simulated by two SEBALMC models and the CaneSim® model, compared to values measured in the field for both seasons are shown. Raw field data (open symbols) were adjusted to account for spatial within-field variation (closed symbols).

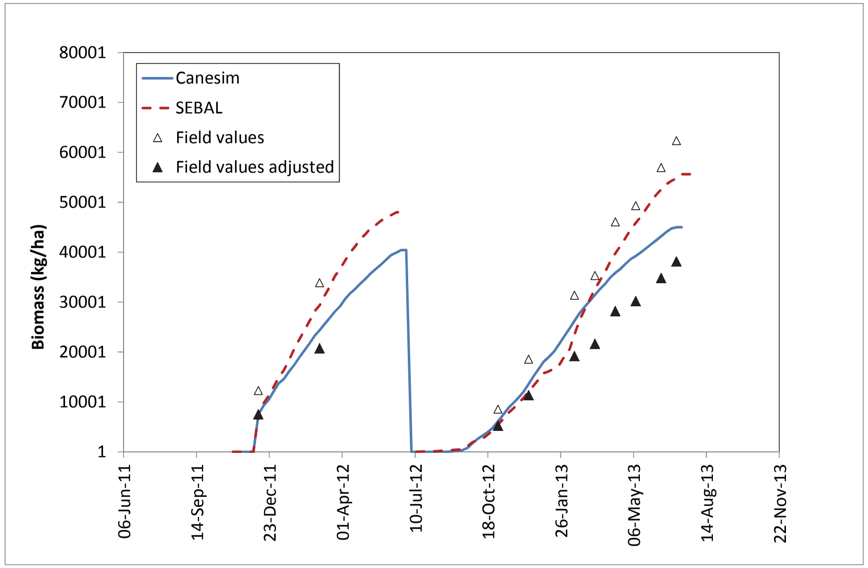
The results shown below are in addition to that shown in Chapter 3.

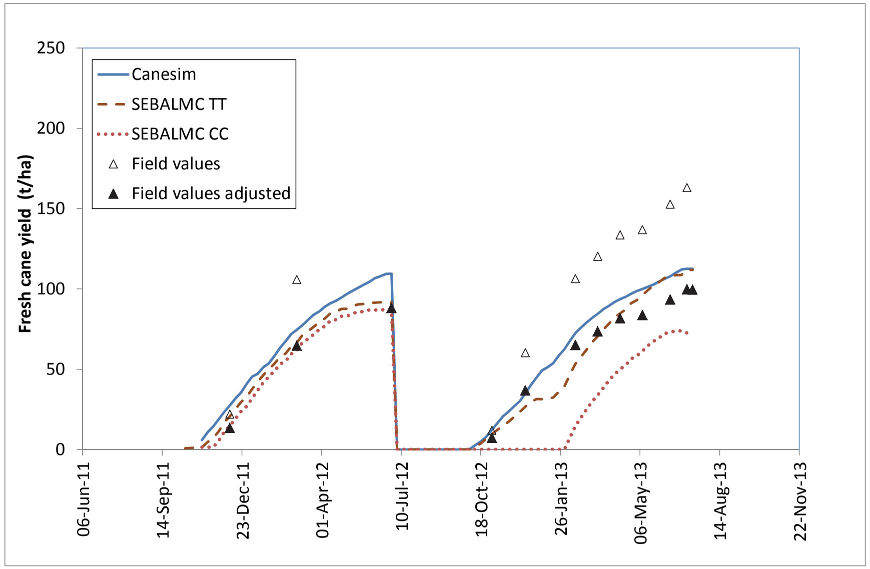
Farm A, Field 8A

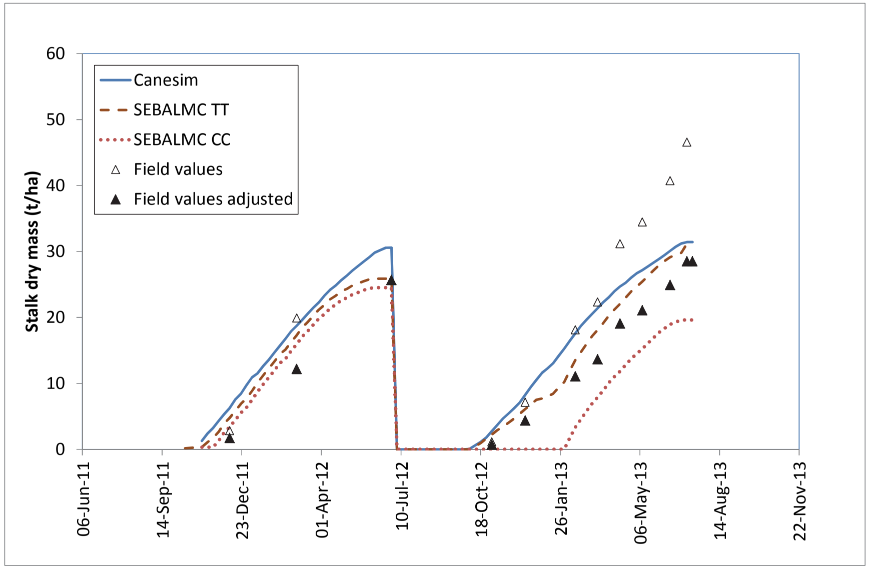


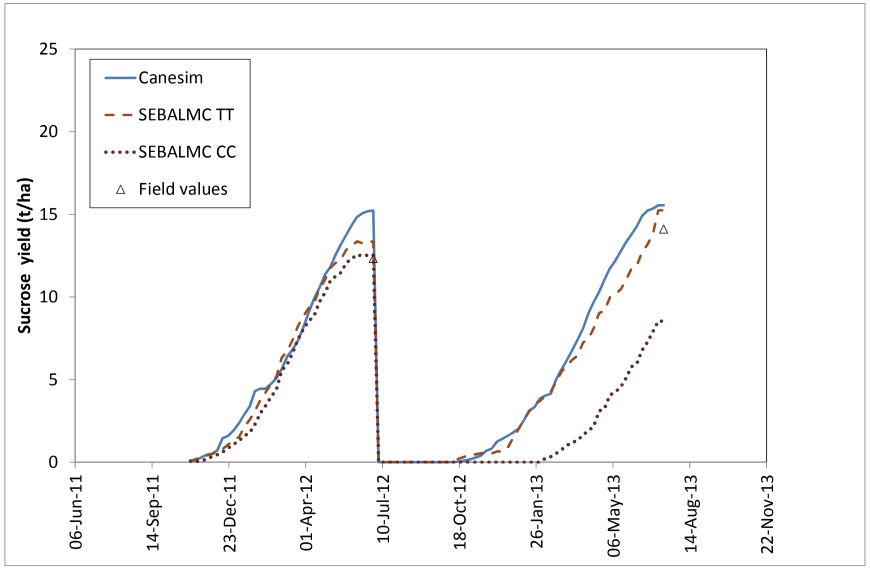


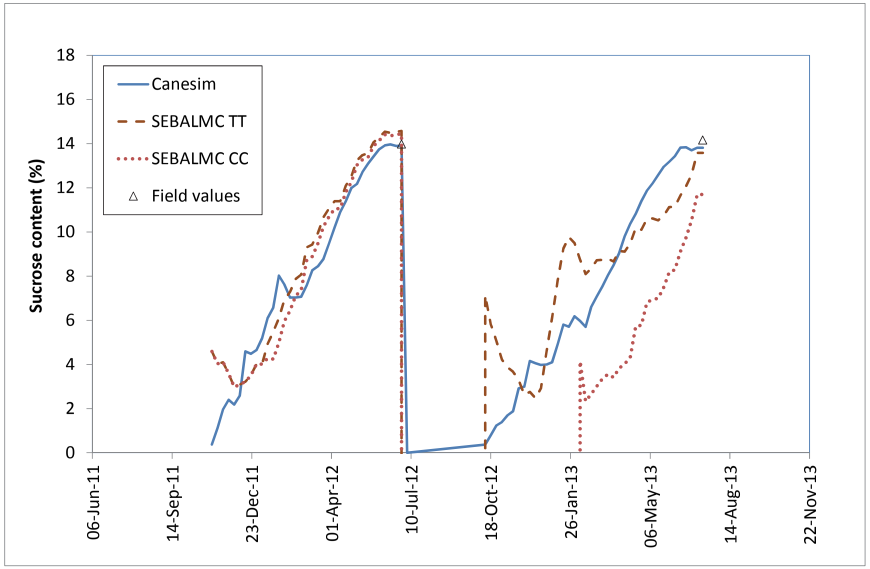




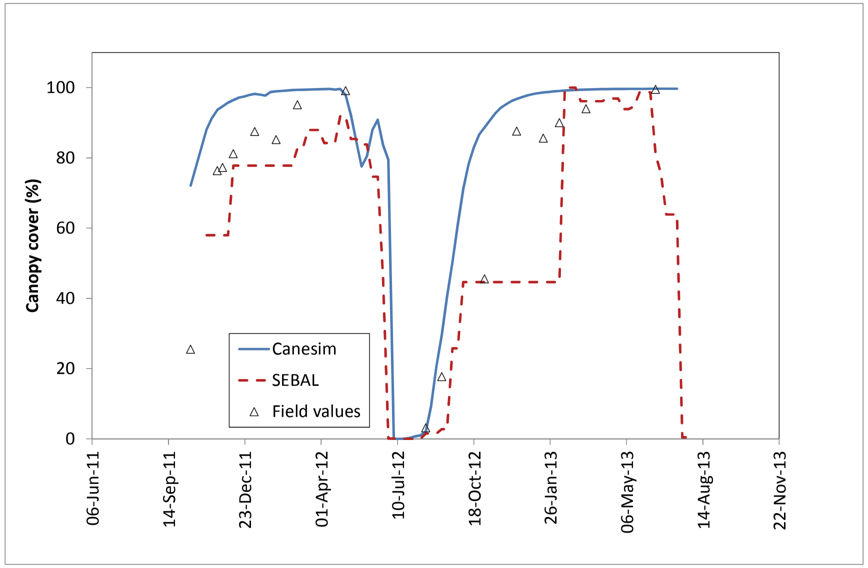

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
0
50
100
150
200
250
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

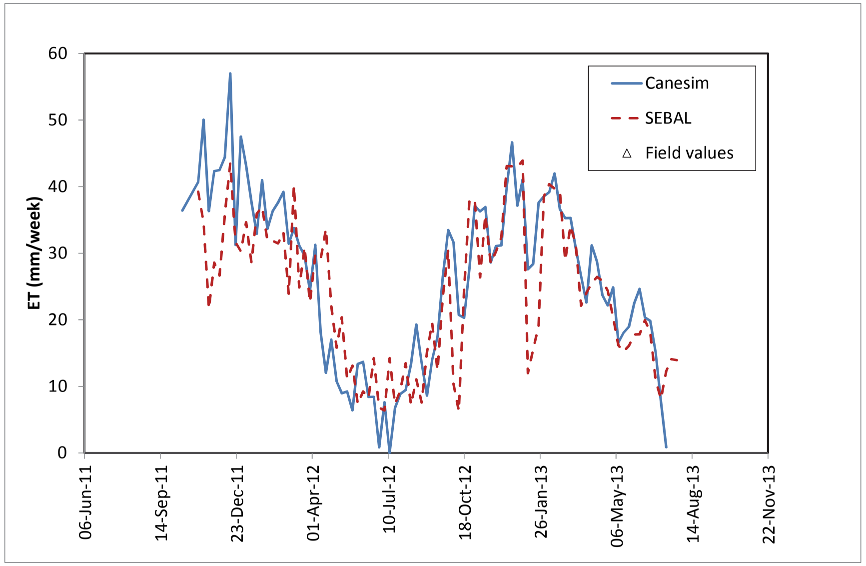

Stalk dry mass (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
0
10
20
30
40
50
60
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

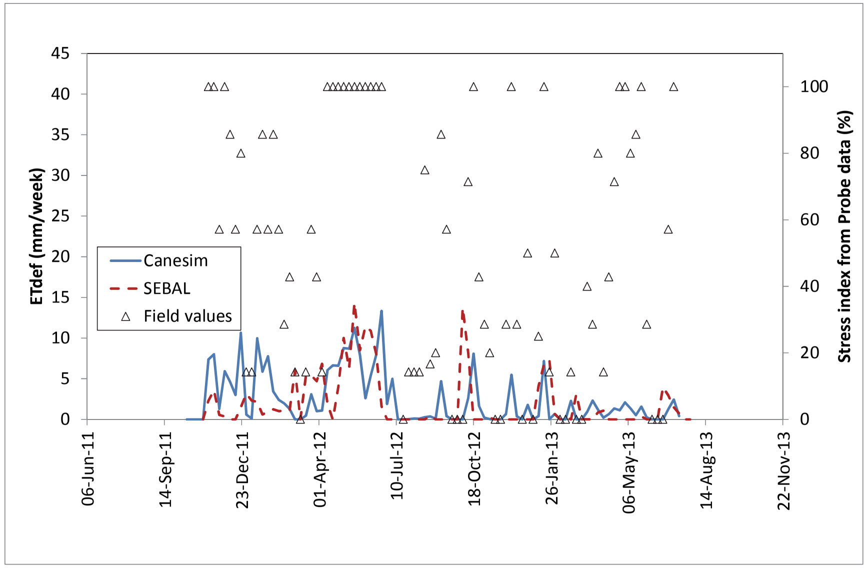

Sucrose yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
0
5
10
15
20
25
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

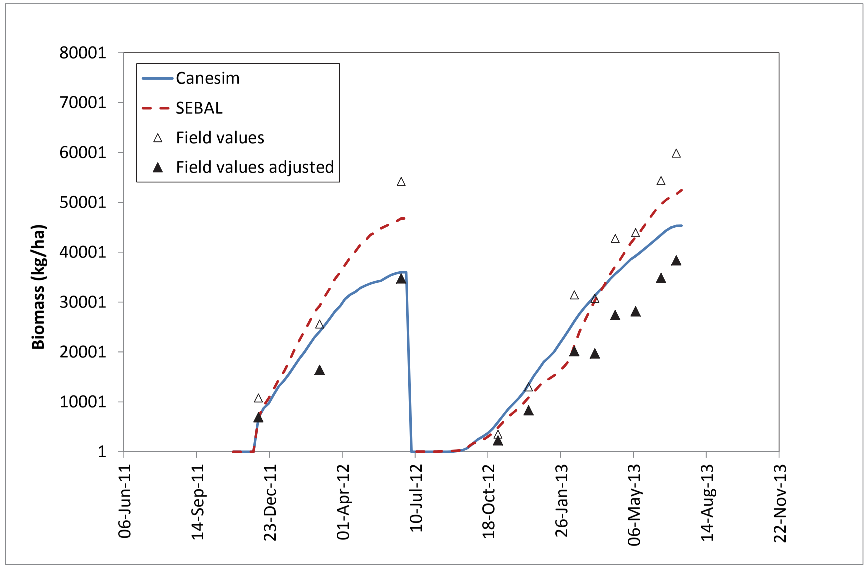

Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
0
2
4
6
8
10
12
14
16
18
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

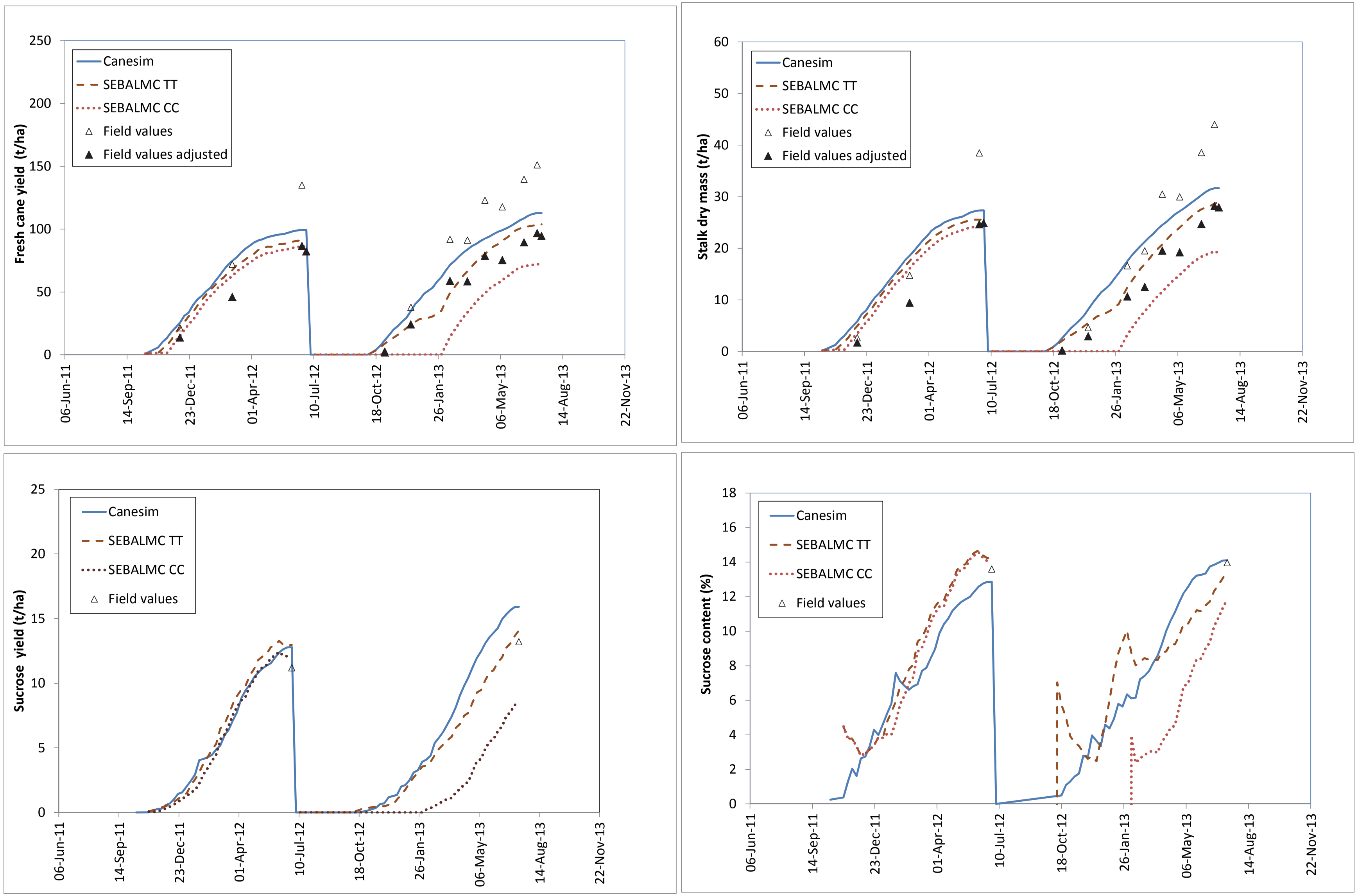
Farm A, Field 8C



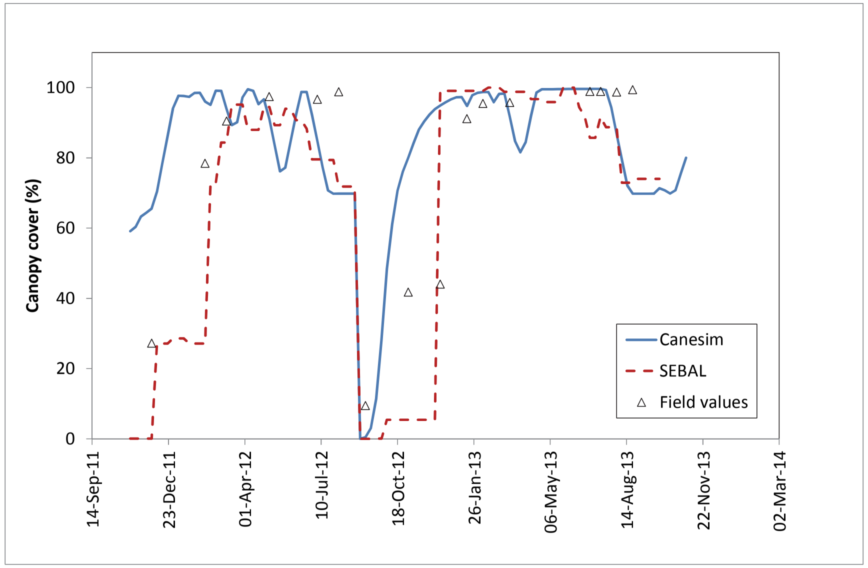


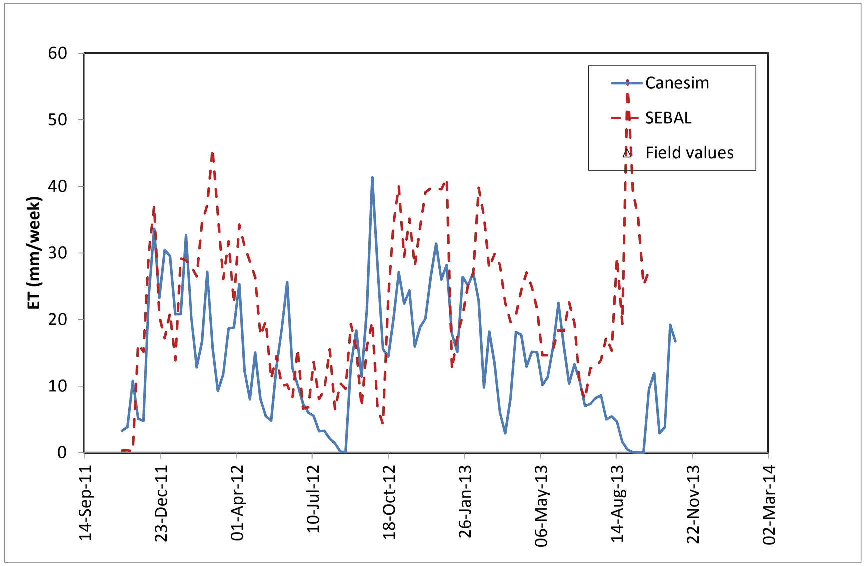


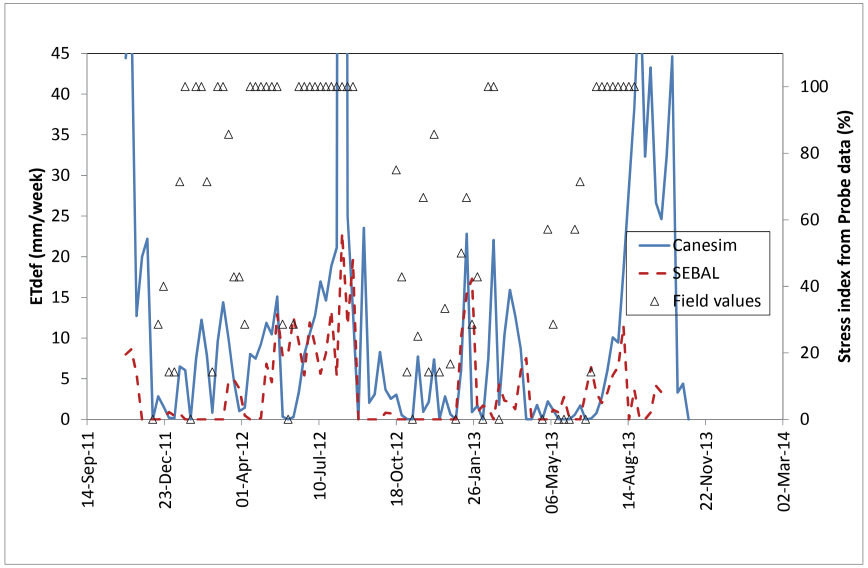


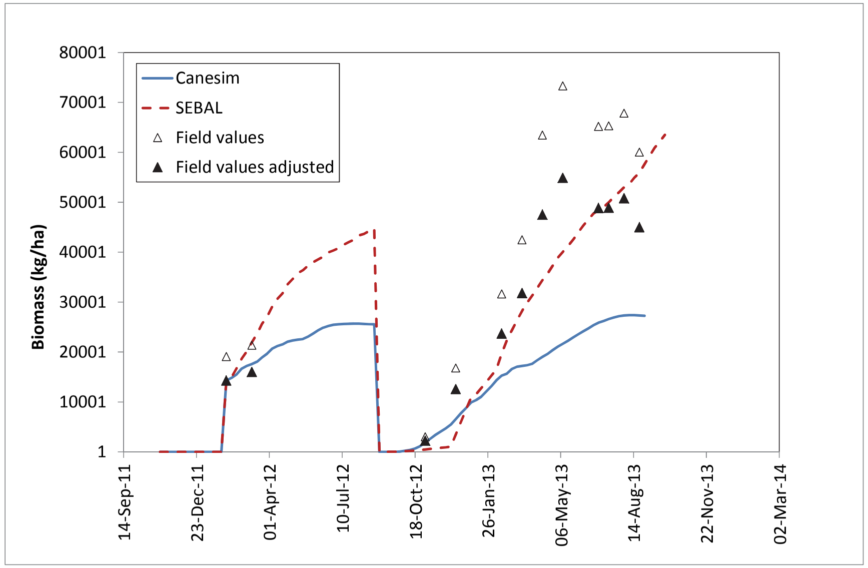

Fresh cane yield (t/ha)
0
50
100
150
200
250
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
Stalk dry mass (t/ha)
0
10
20
30
40
50
60
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
Sucrose yield (t/ha)
0
5
10
15
20
25
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
Sucrose content (%)
0
2
4
6
8
10
12
14
16
18
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

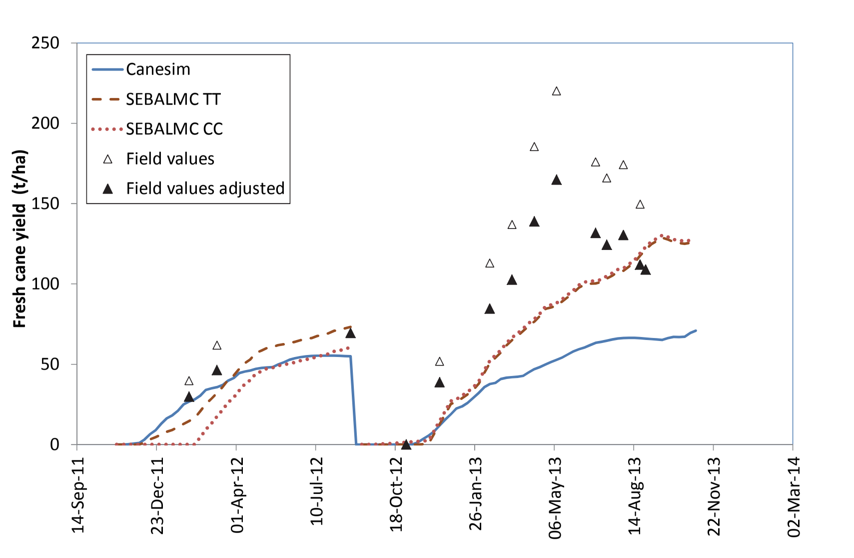
Farm B, Field 17

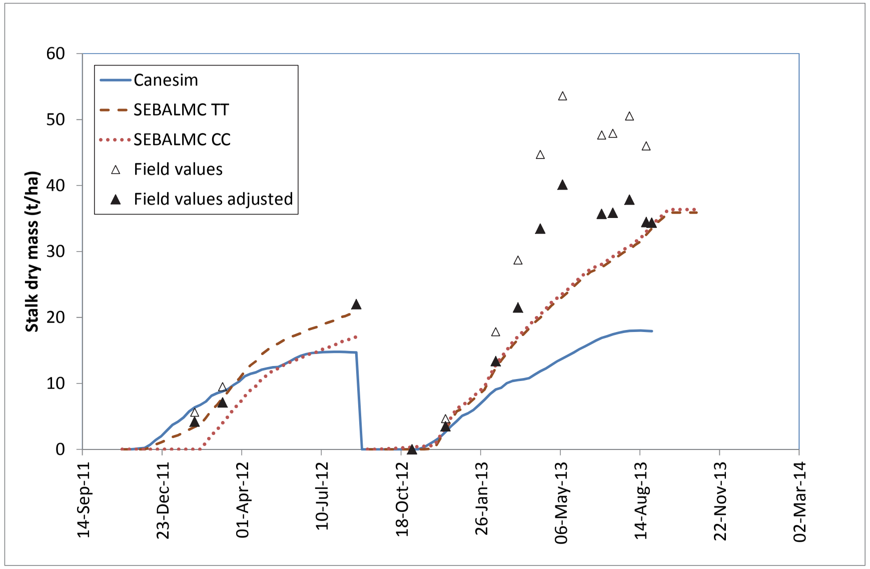


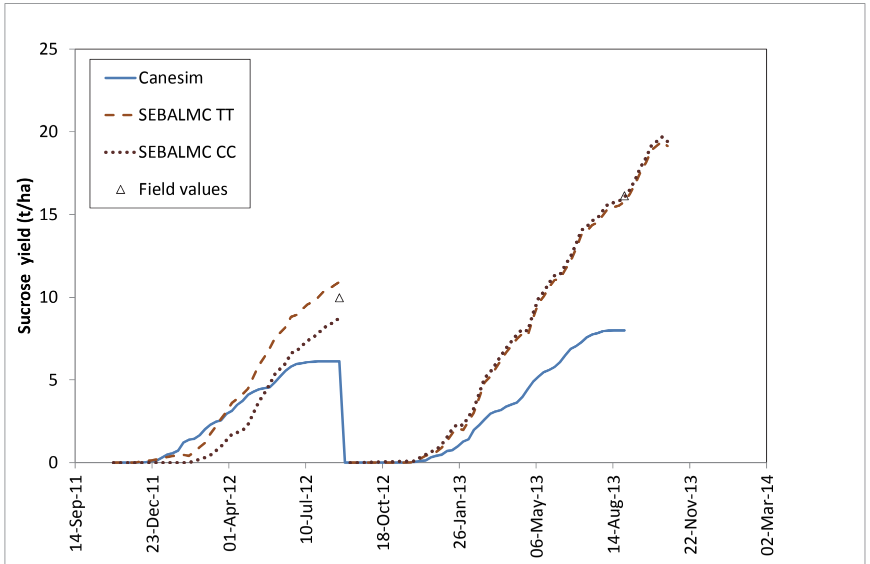


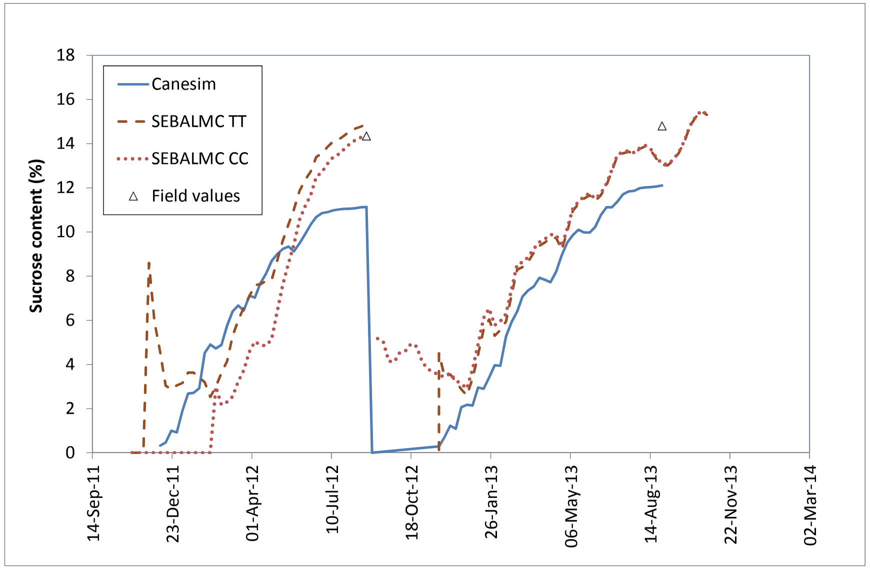




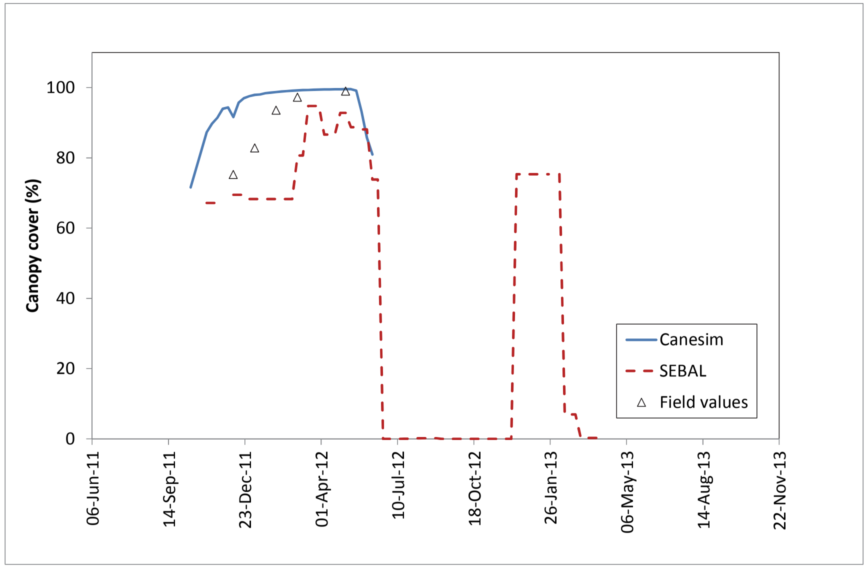

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

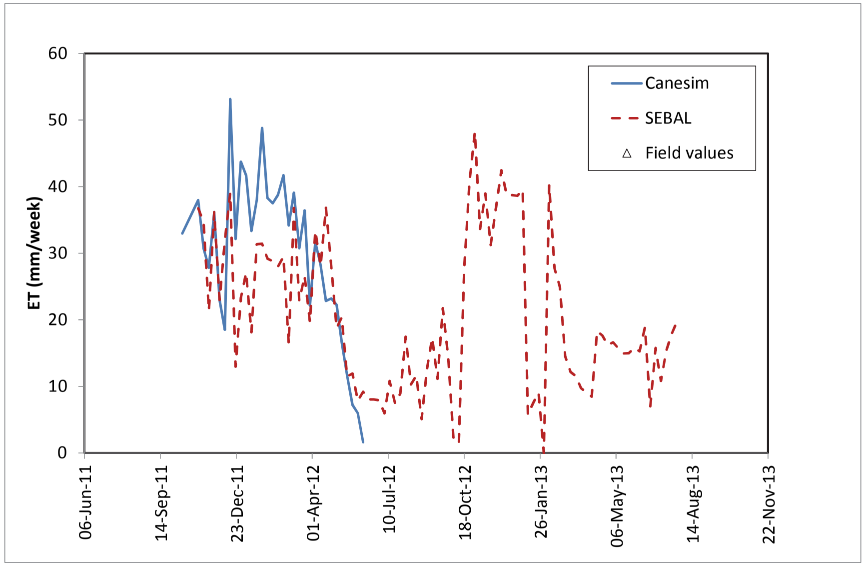

Stalk dry mass (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

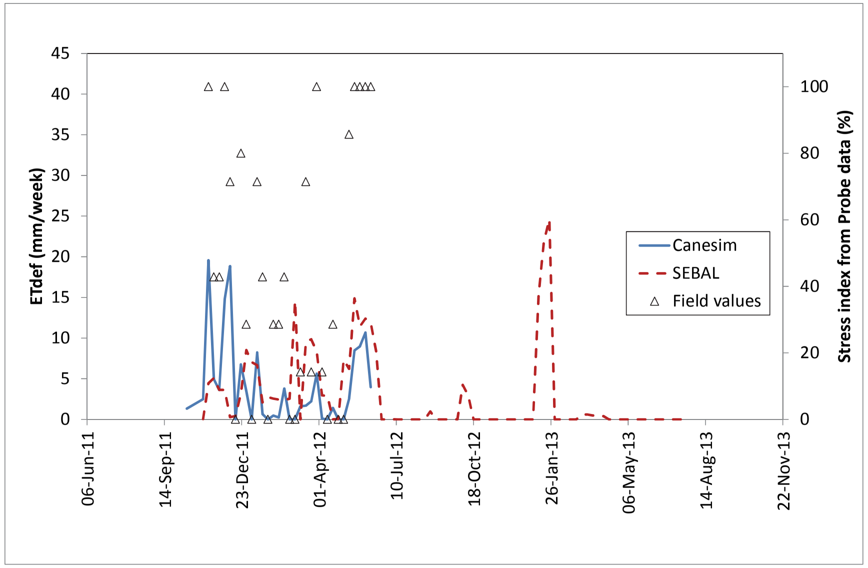

Sucrose yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

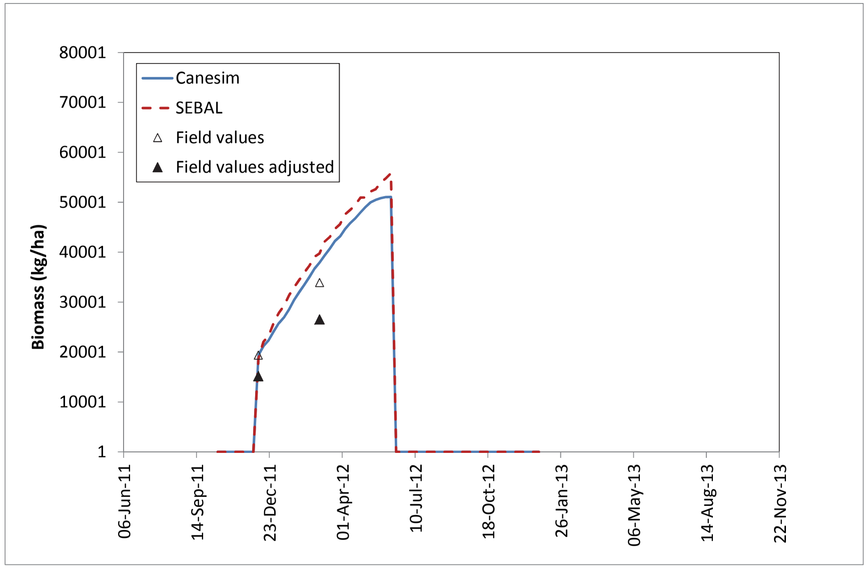

Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

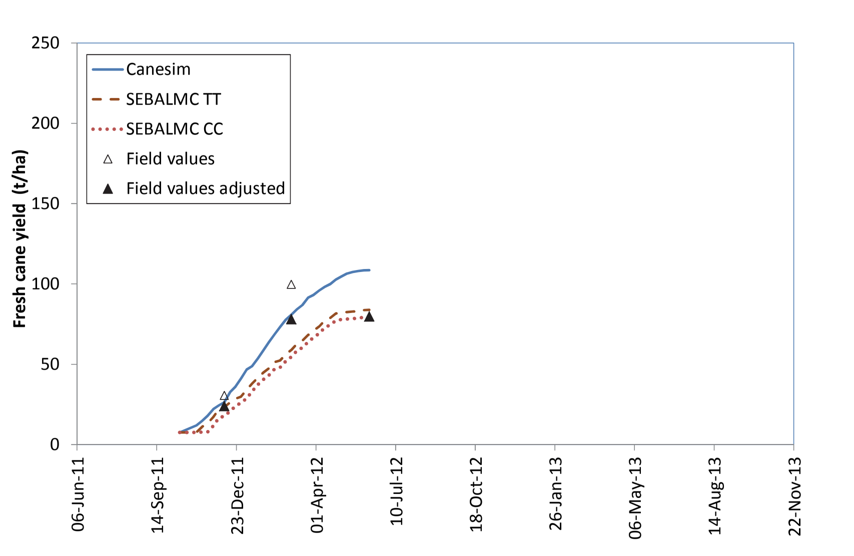
Farm C, Field 7

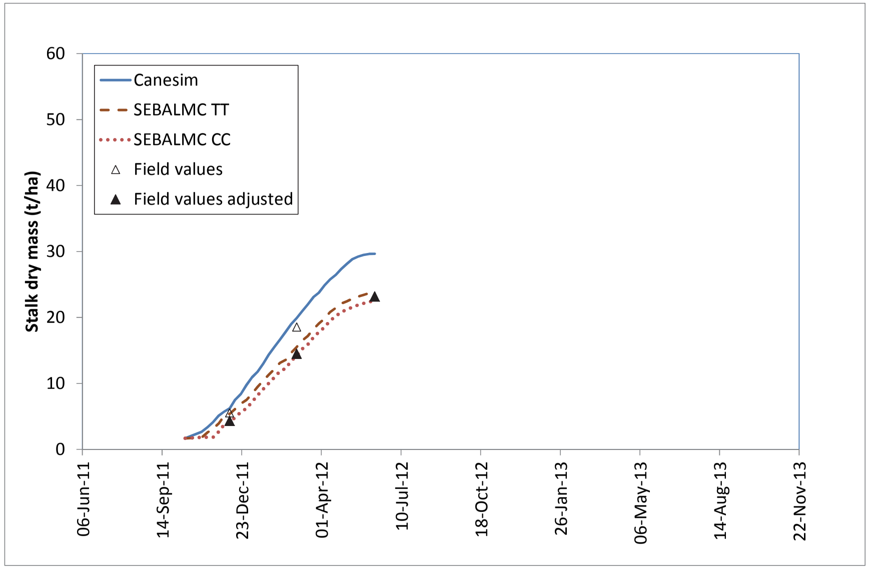


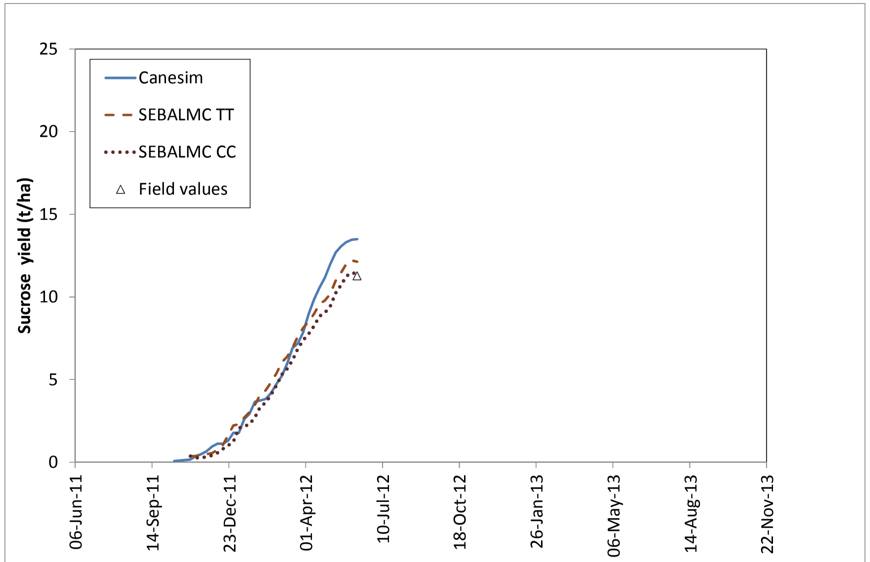


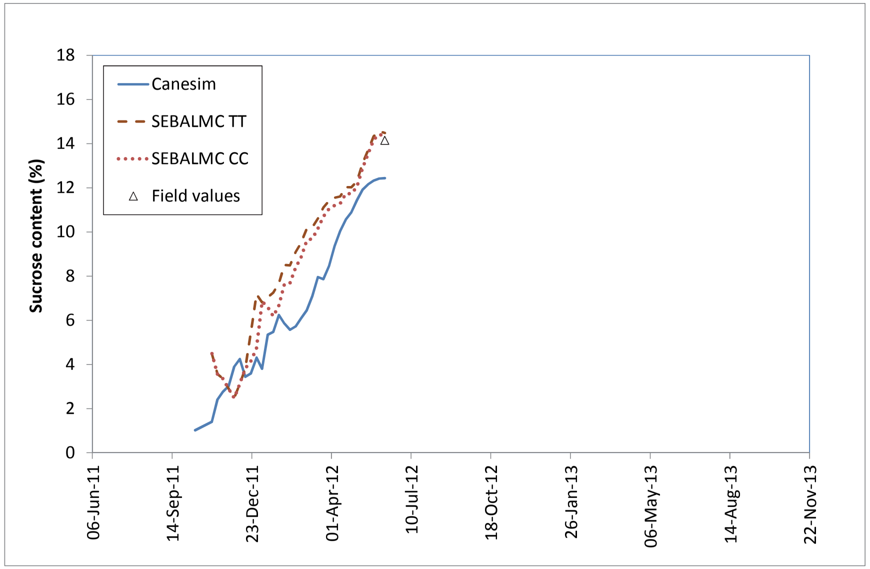




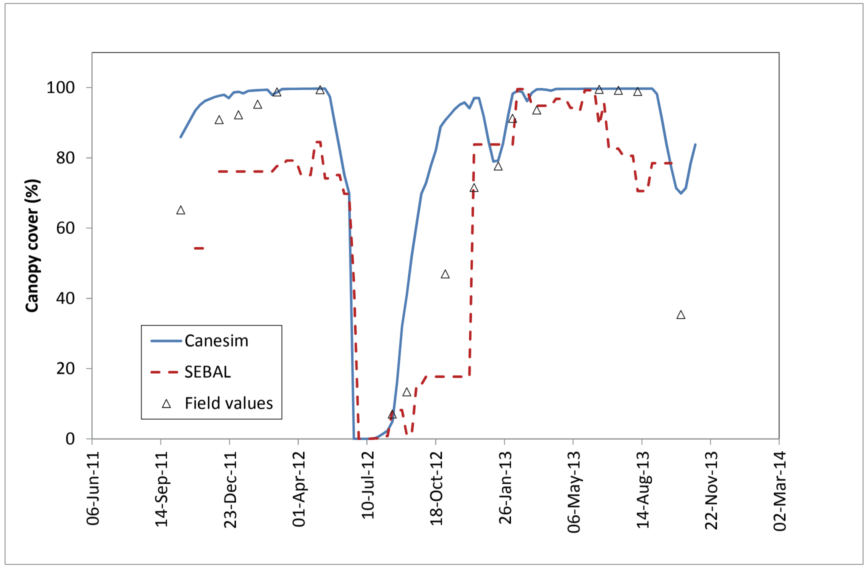

Fresh cane yield (t/ha)
250
200
150
100
50
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

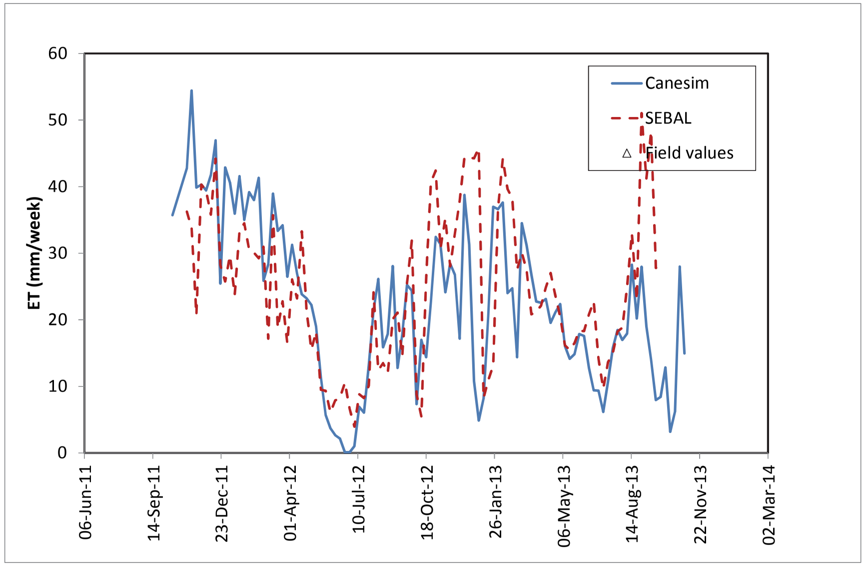

Stalk dry mass (t/ha)
60
50
40
30
20
10
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

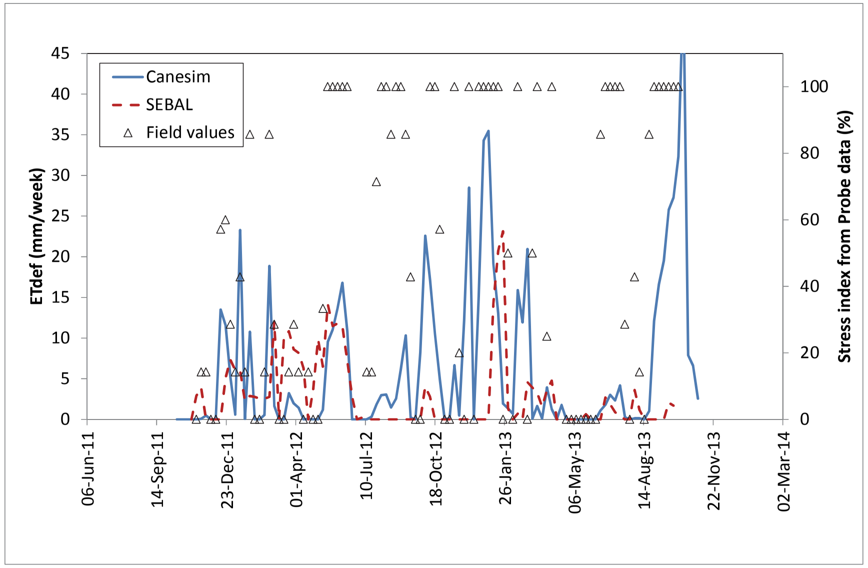

Sucrose yield (t/ha)
25
20
15
10
5
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

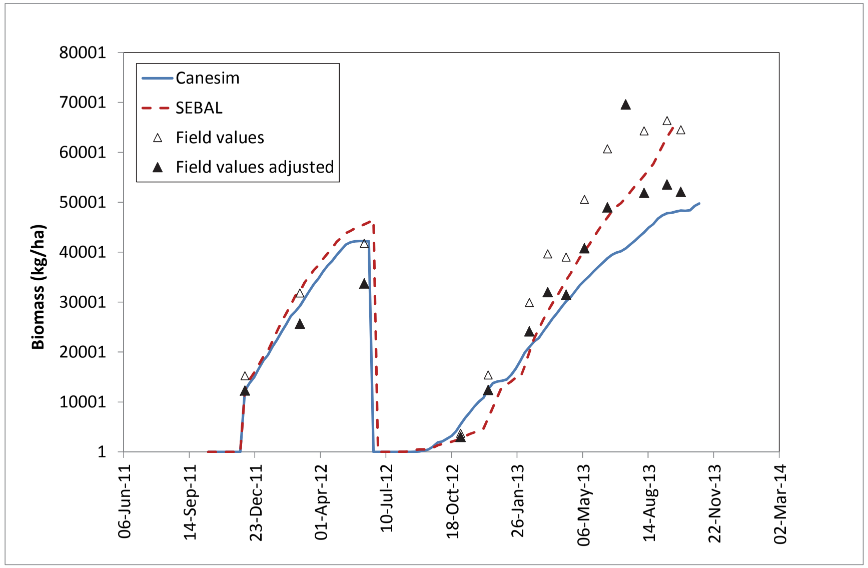

Sucrose content (%)
18
16
14
12
10
8
6
4
2
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

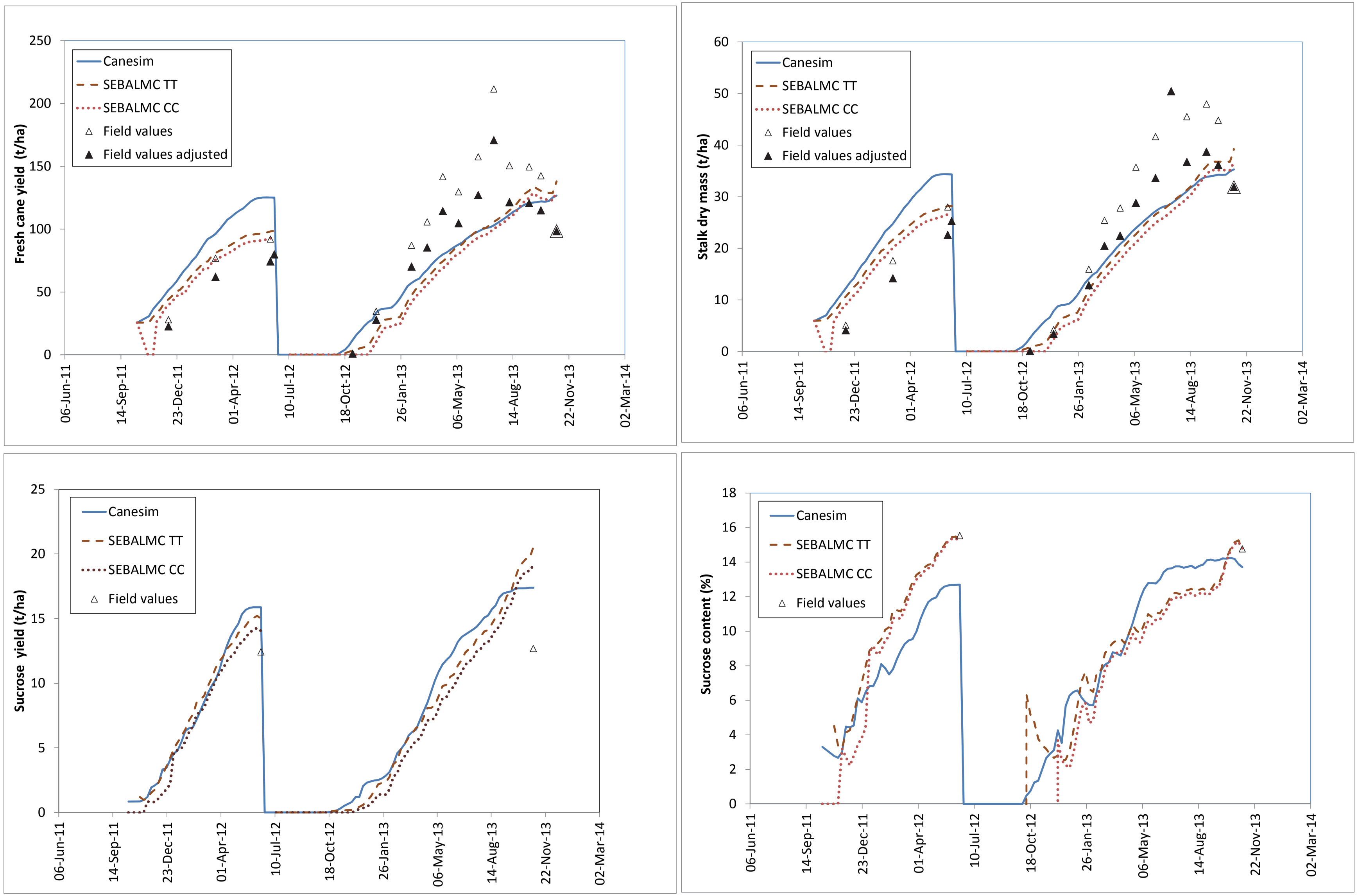
Farm C, Field 3B



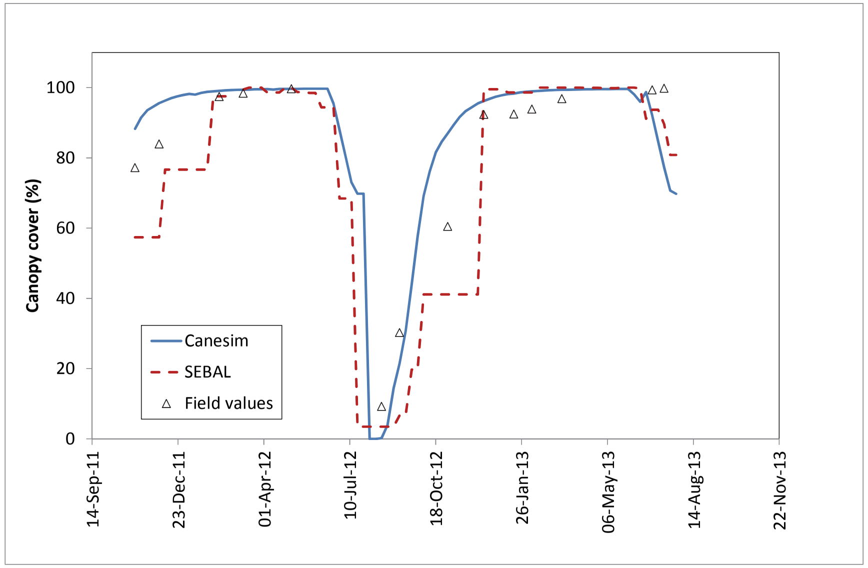


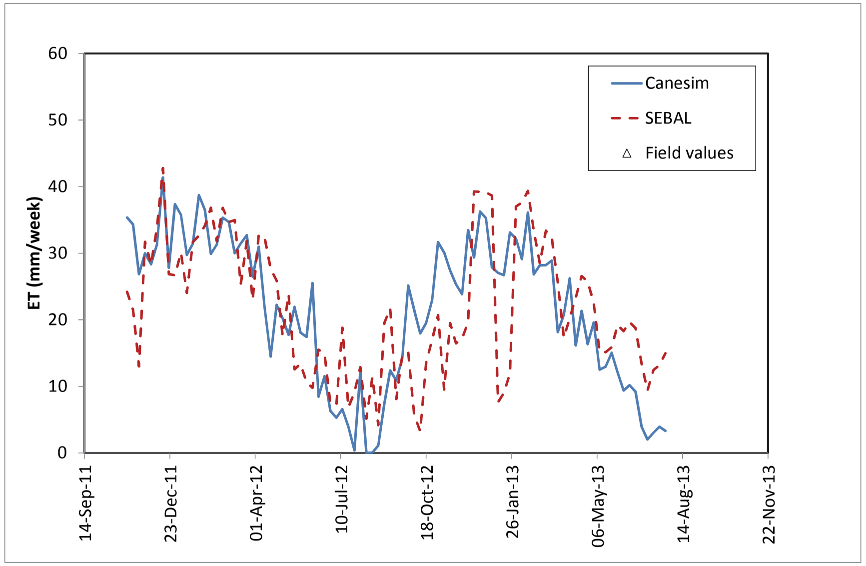


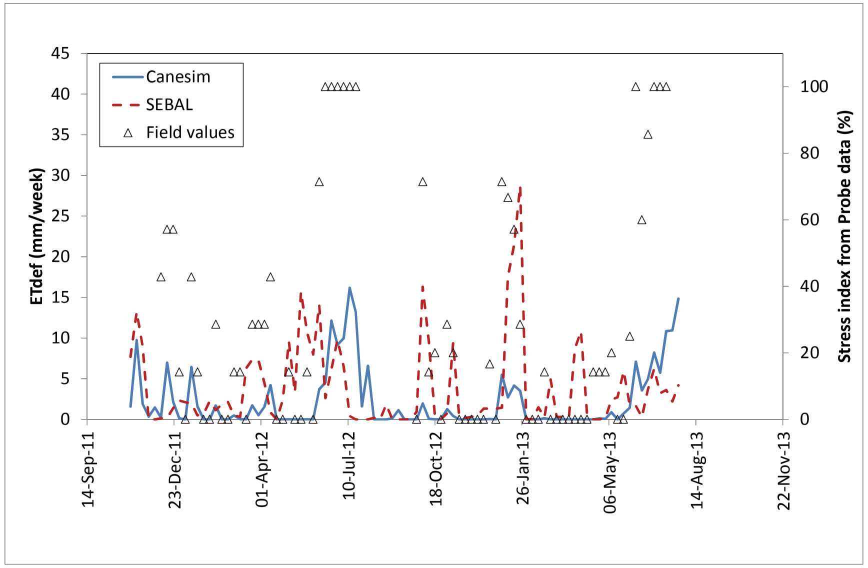


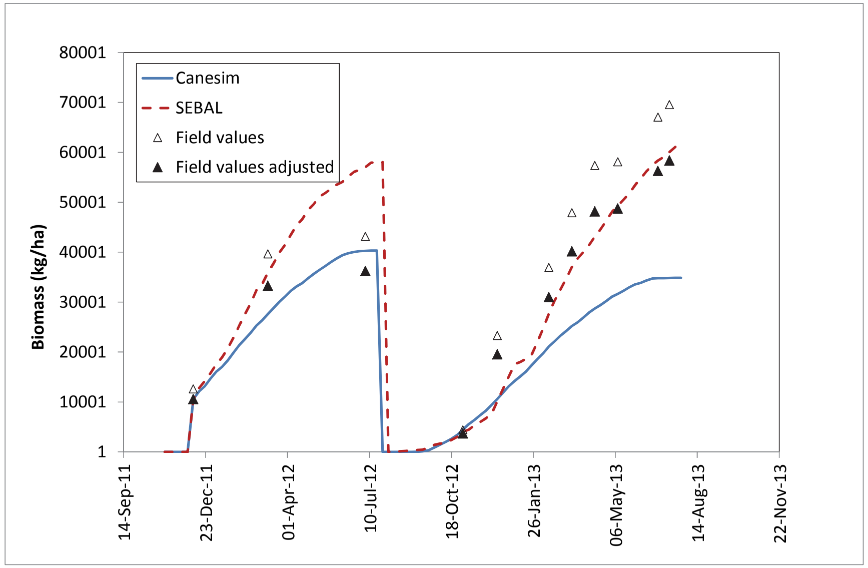

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
Stalk dry mass (t/ha)
Sucrose yield (t/ha)
Sucrose content (%)
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

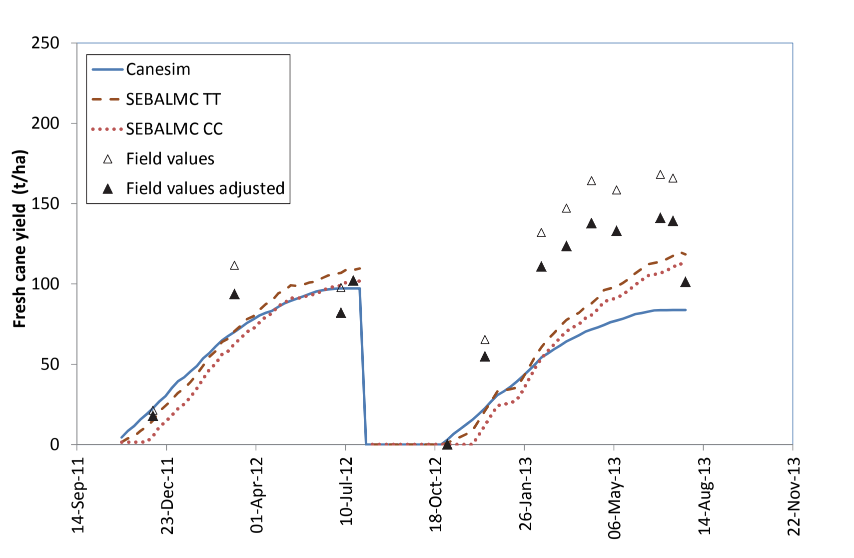
Farm D, Field 12

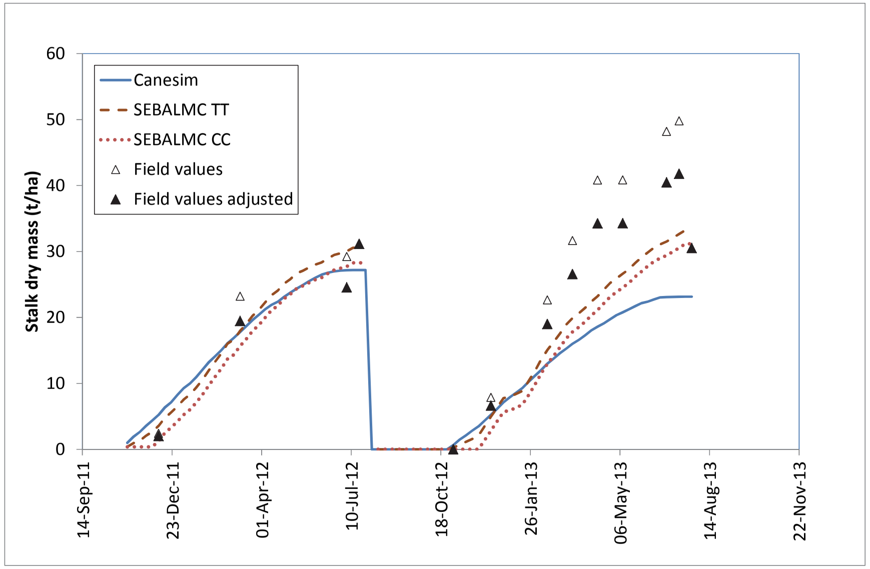


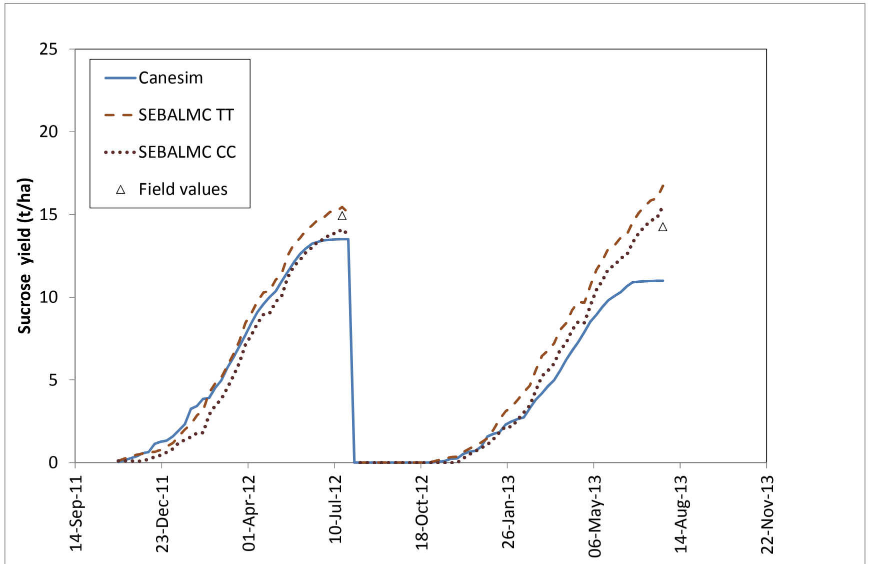


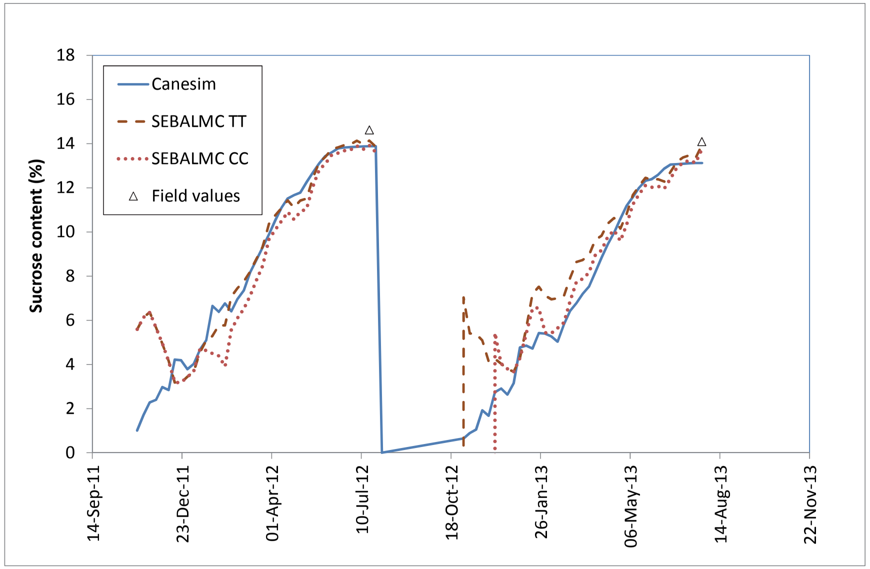




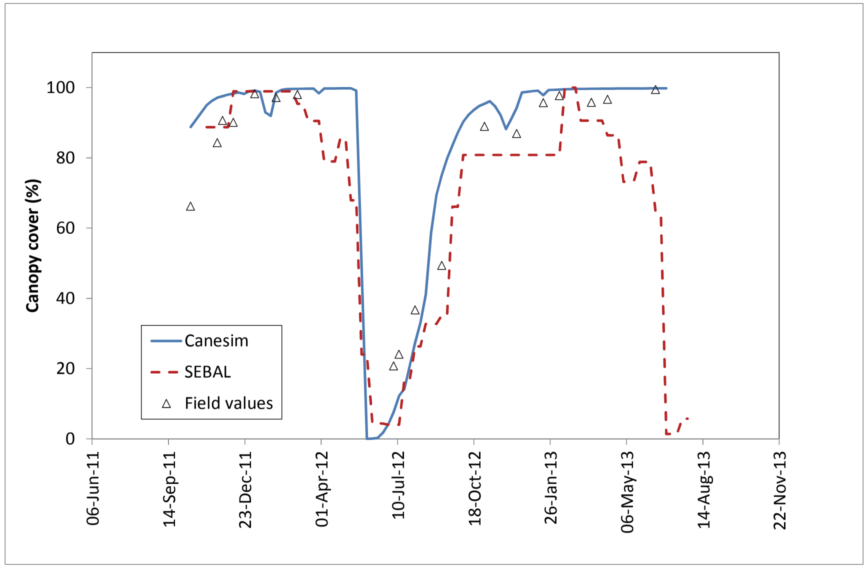

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

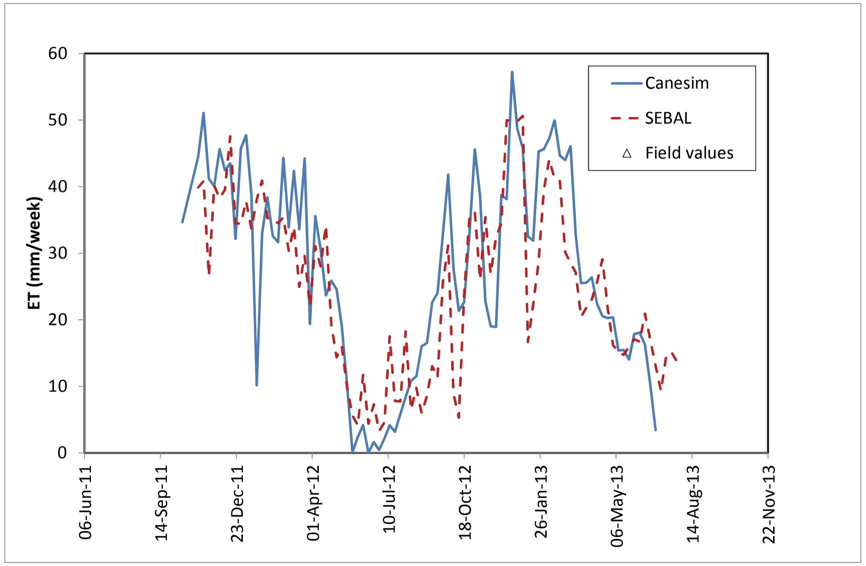

Stalk dry mass (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

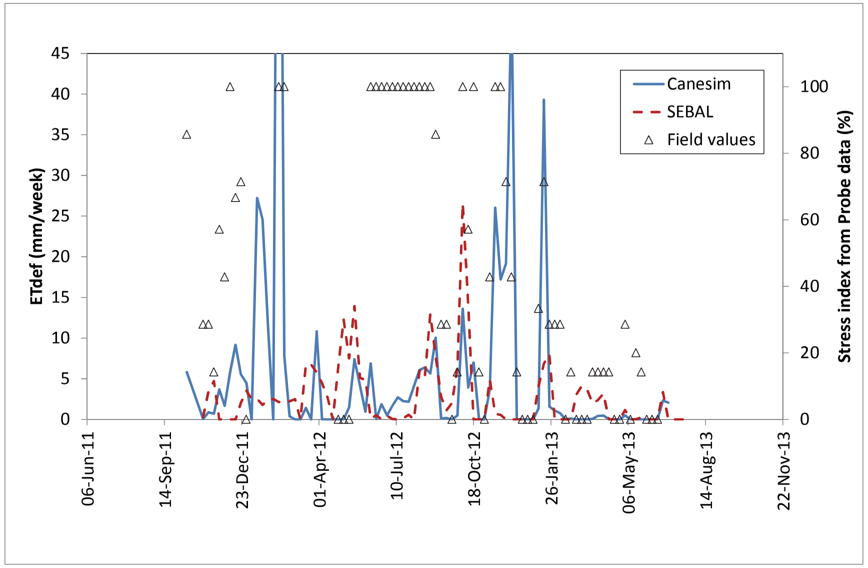

Sucrose yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

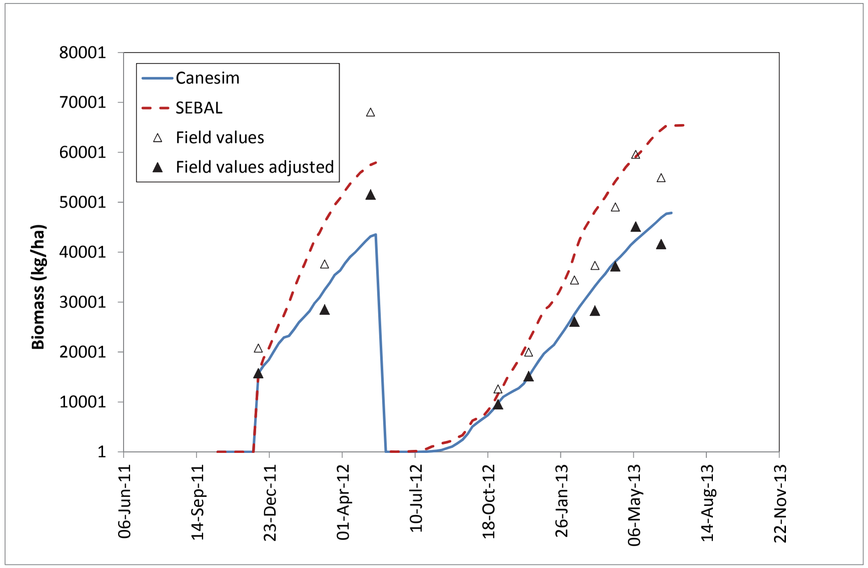

Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

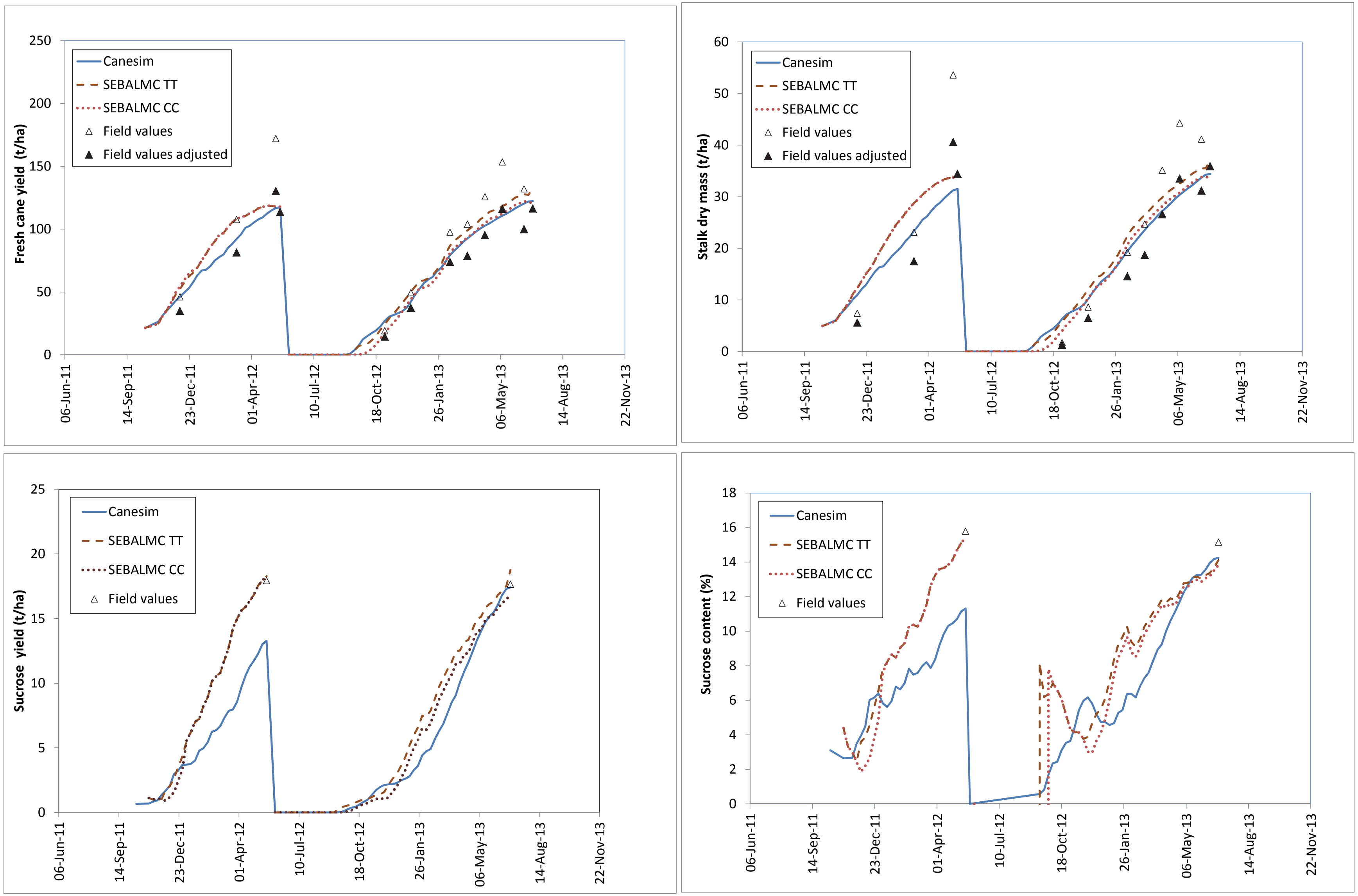
Farm E, Field 70



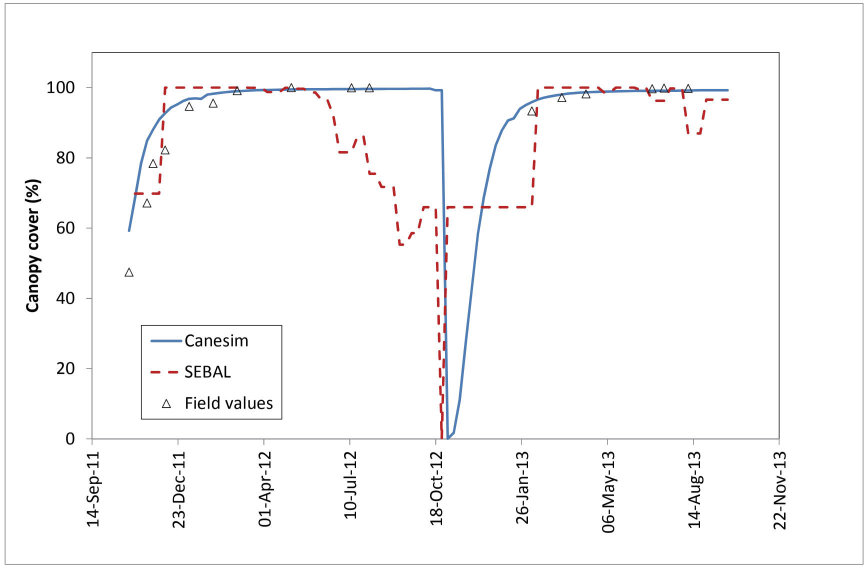


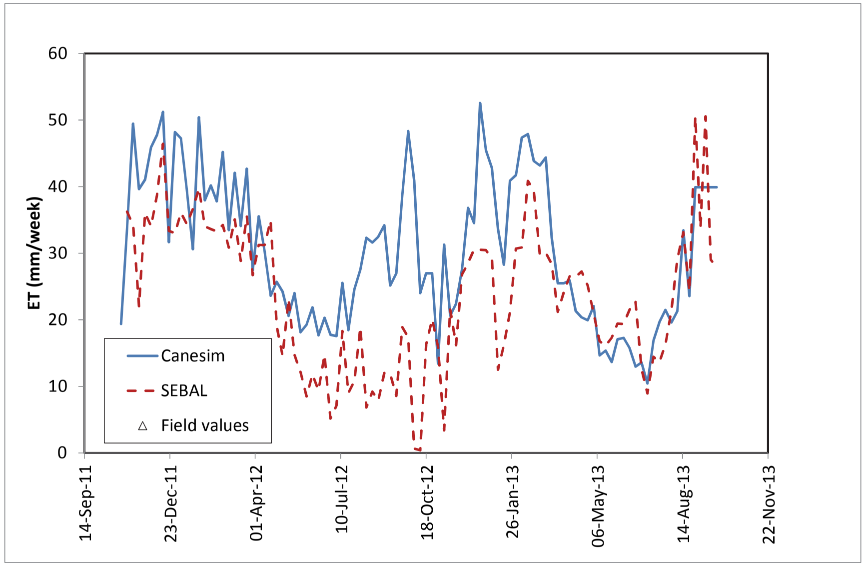


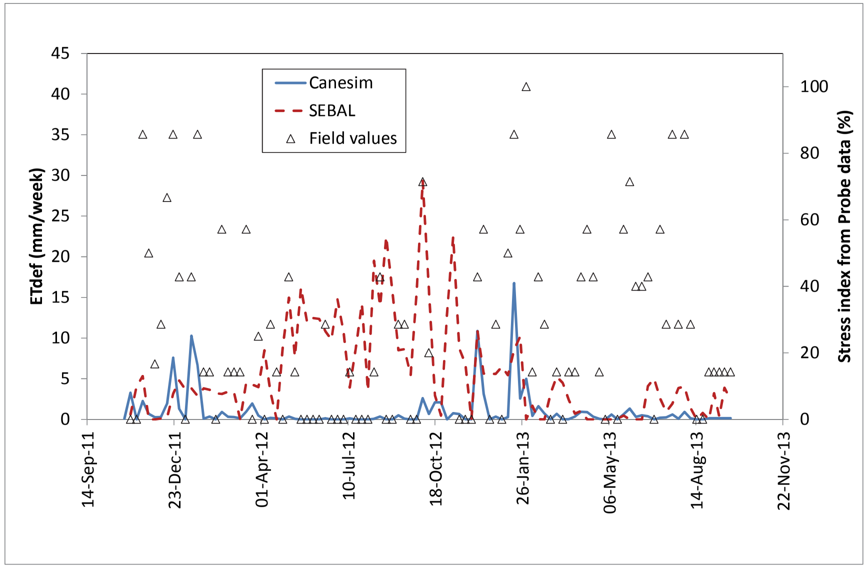


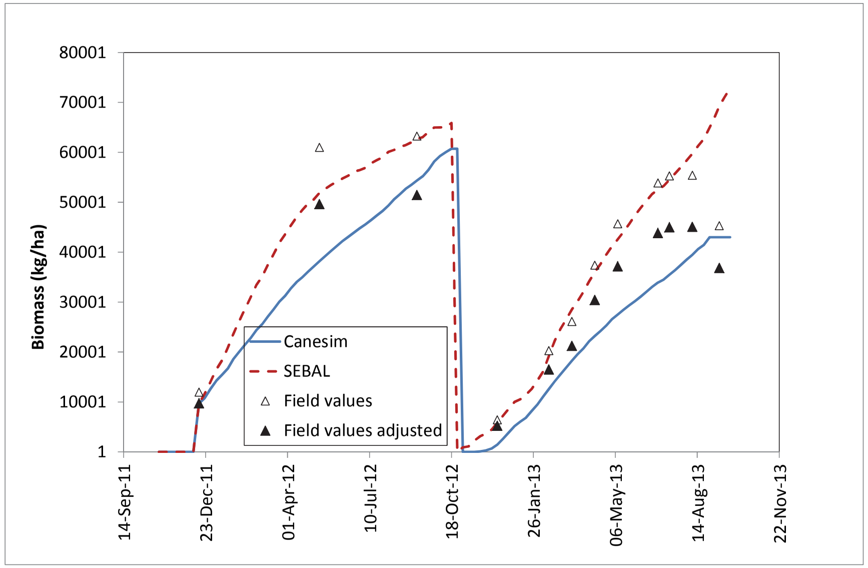

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
Stalk dry mass (t/ha)
Sucrose yield (t/ha)
Sucrose content (%)

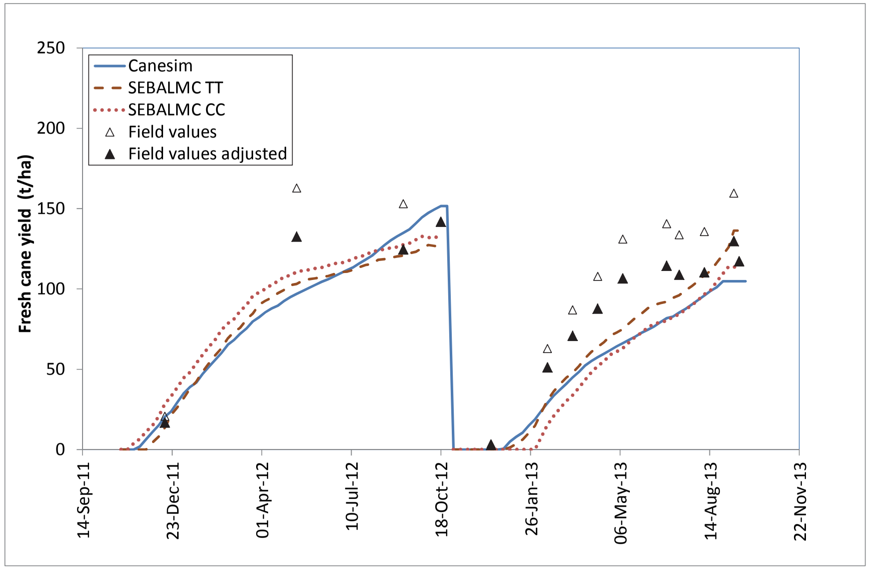
Farm E, Field 72

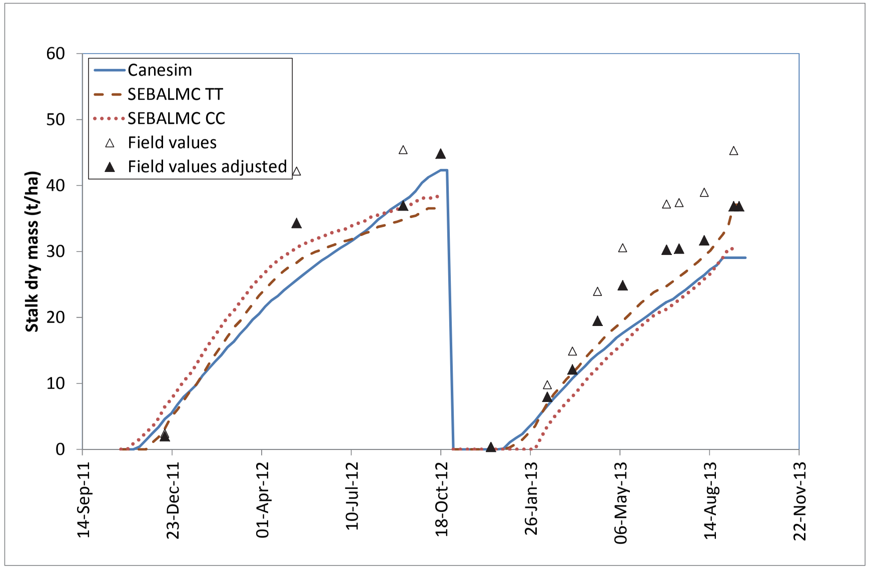


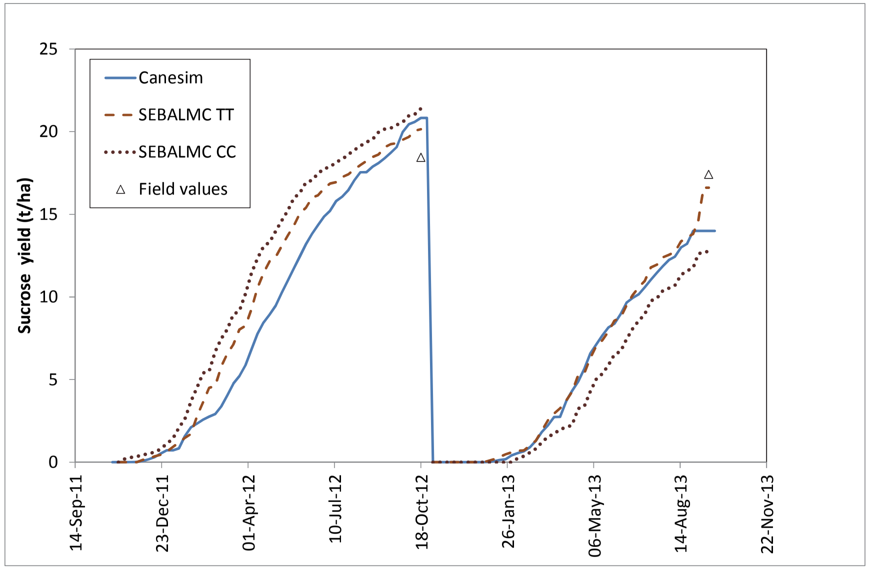


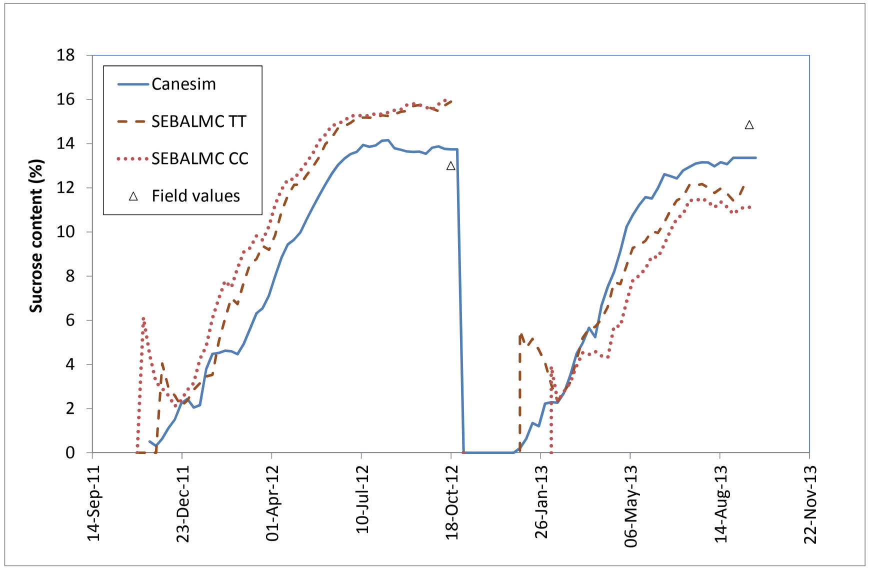




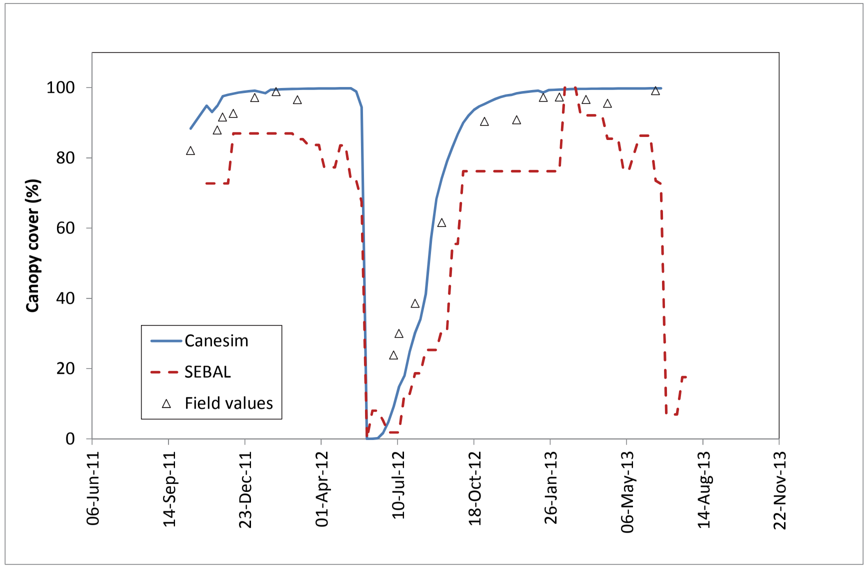

Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
250
200
150
100
50
0
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

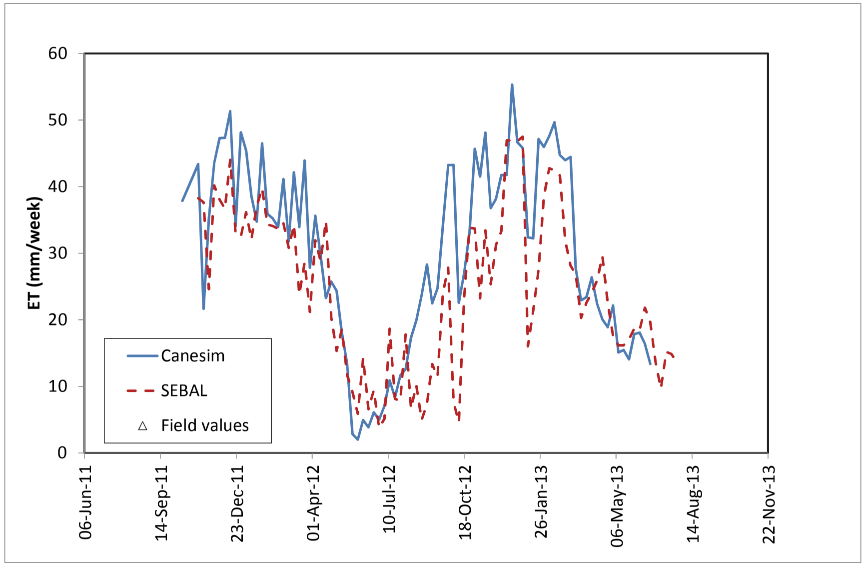

Stalk dry mass (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
60
50
40
30
20
10
0
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

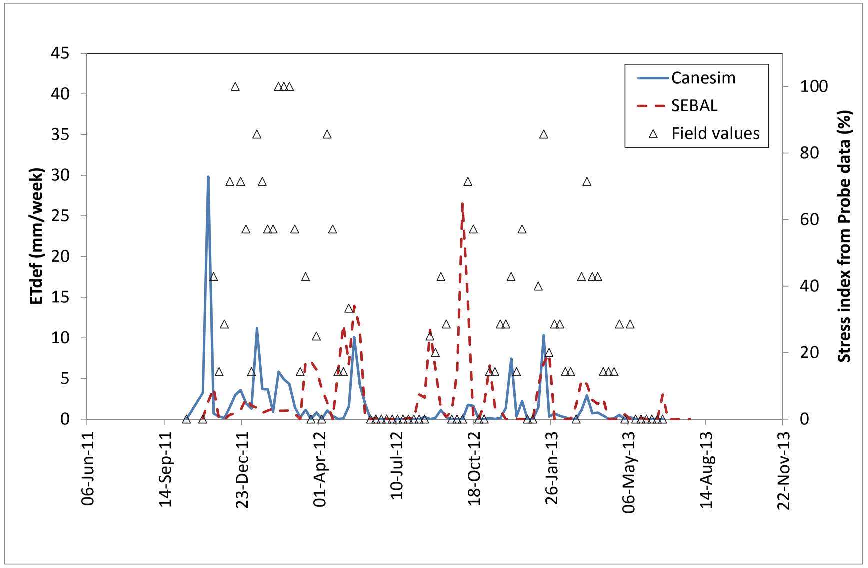

Sucrose yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
25
20
15
10
5
0
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

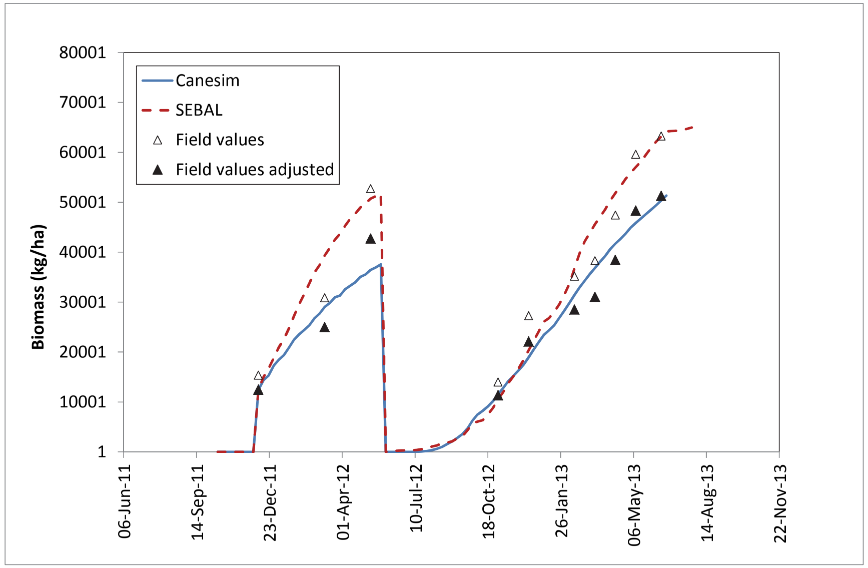

Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
18
16
14
12
10
8
6
4
2
0
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

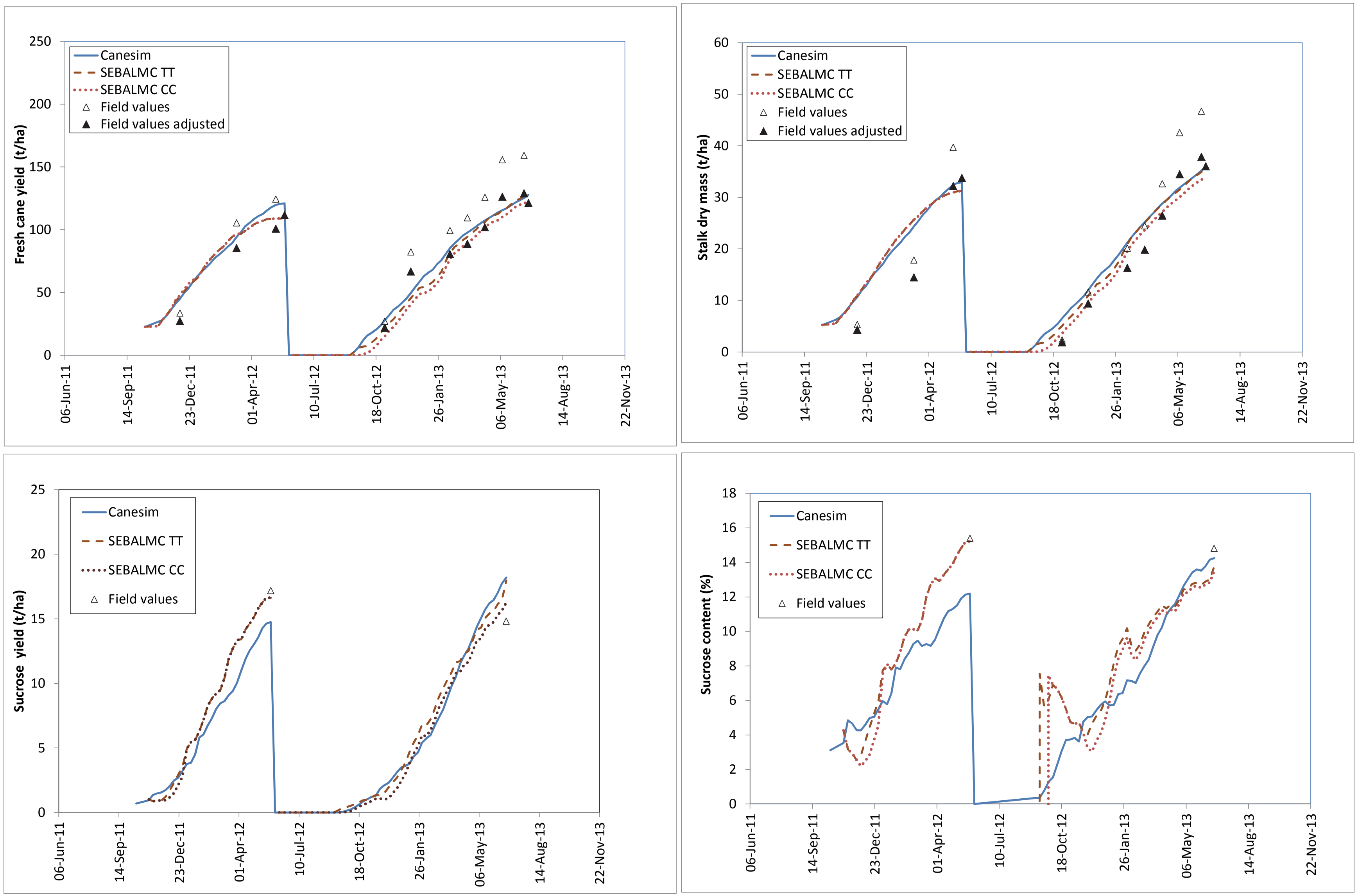
Farm E, Field 81



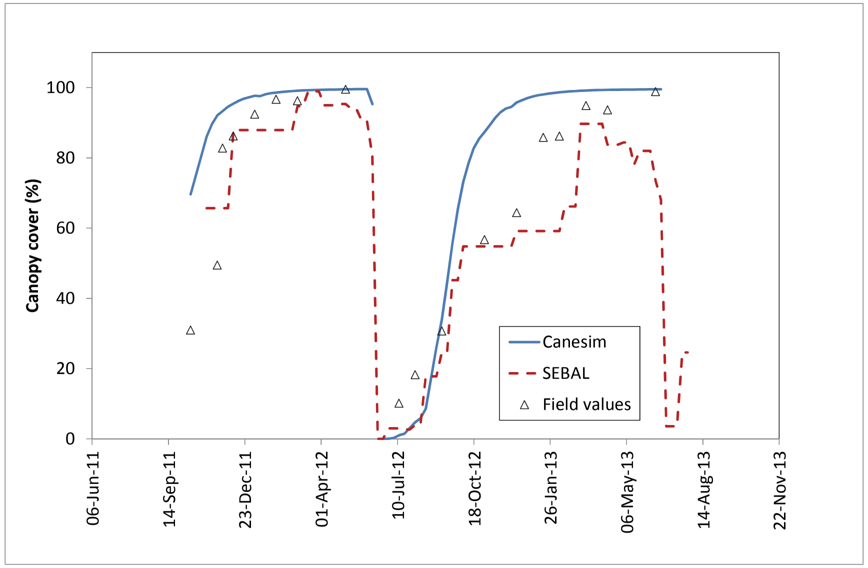


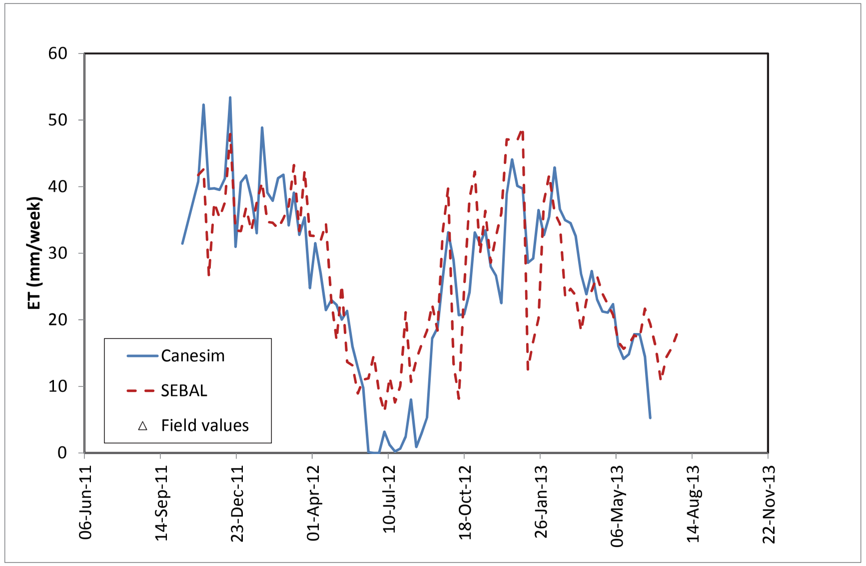


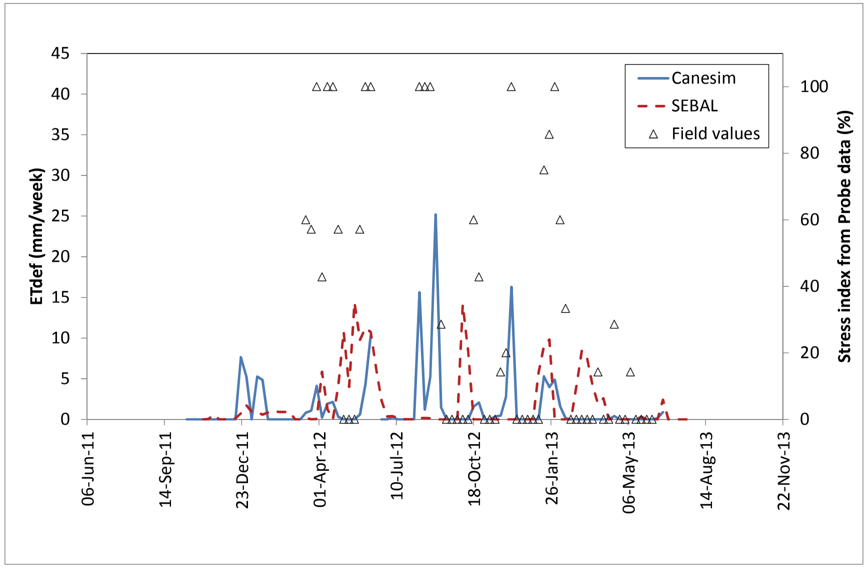


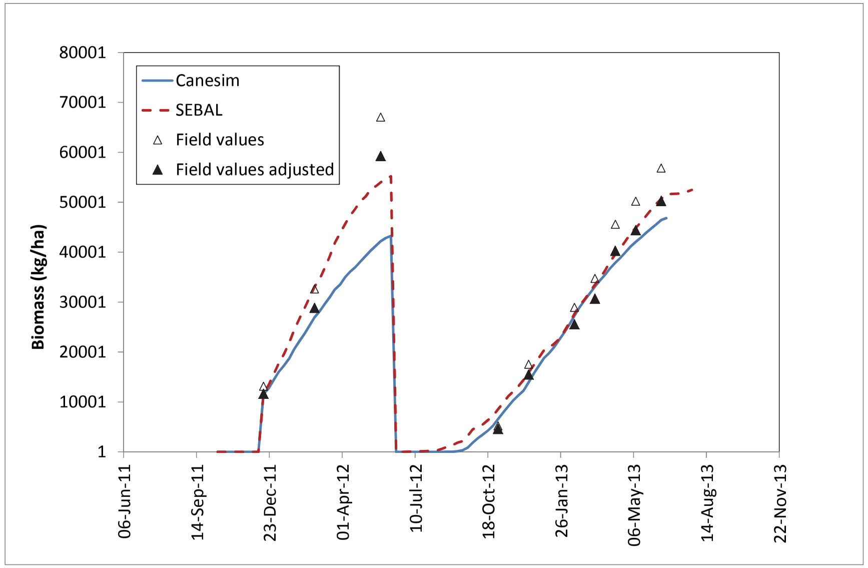

Fresh cane yield (t/ha)
Stalk dry mass (t/ha)
Sucrose yield (t/ha)
Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

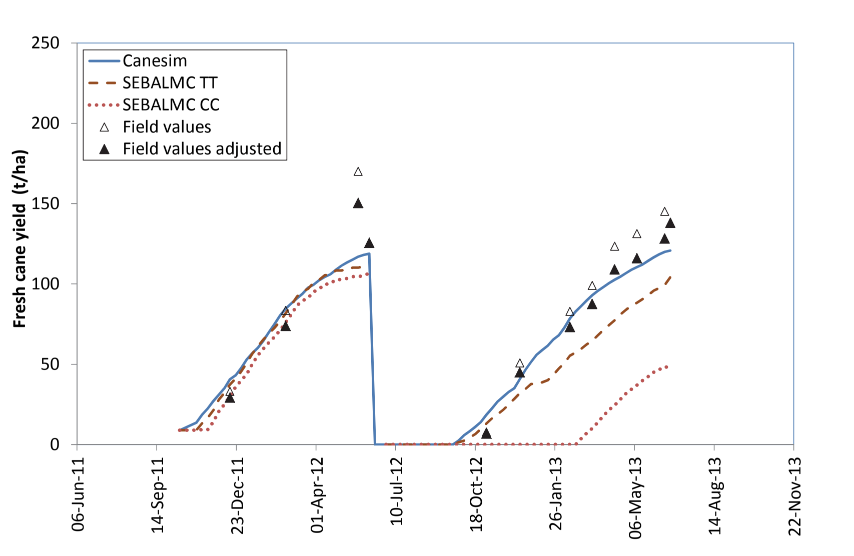
Farm F, Field G4










Fresh cane yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
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10-Jul-12
18-Oct-12
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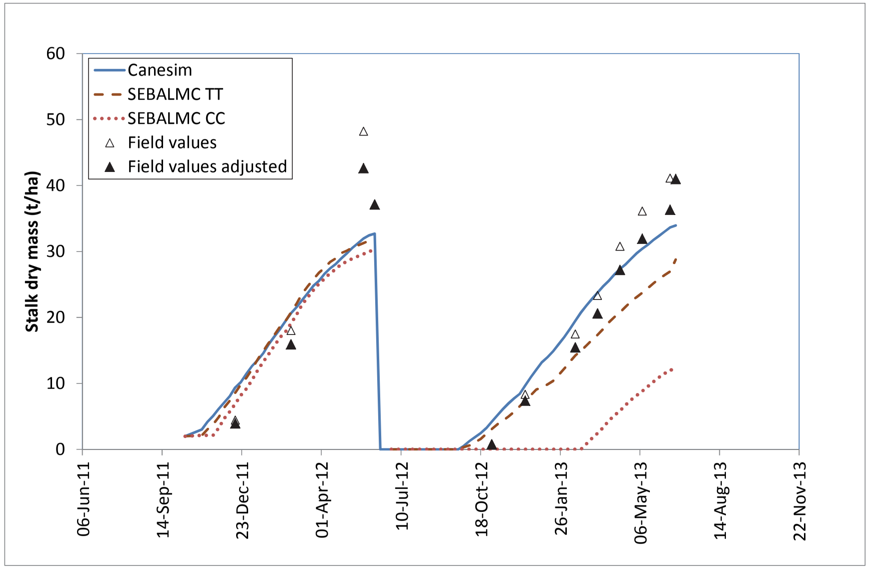
14-Aug-13
22-Nov-13


Stalk dry mass (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
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10-Jul-12
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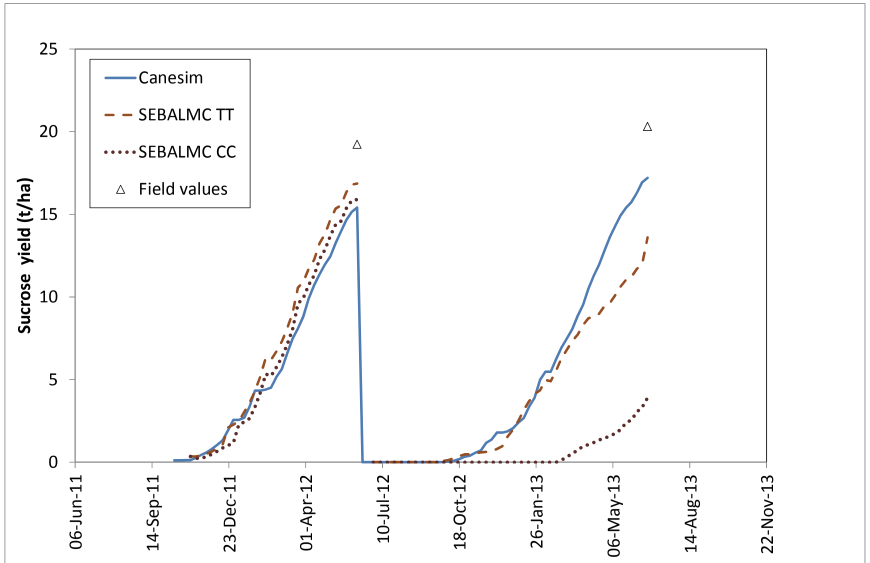
14-Aug-13
22-Nov-13


Sucrose yield (t/ha)
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
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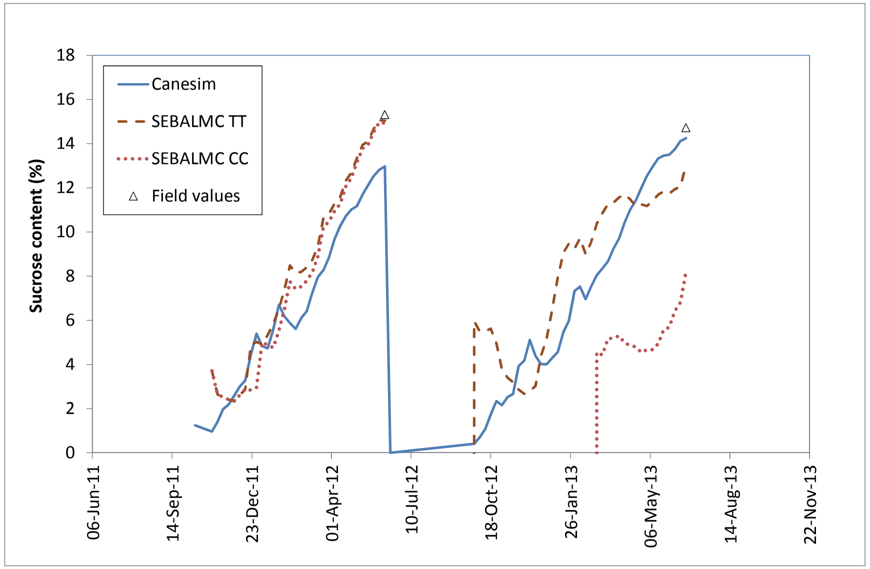
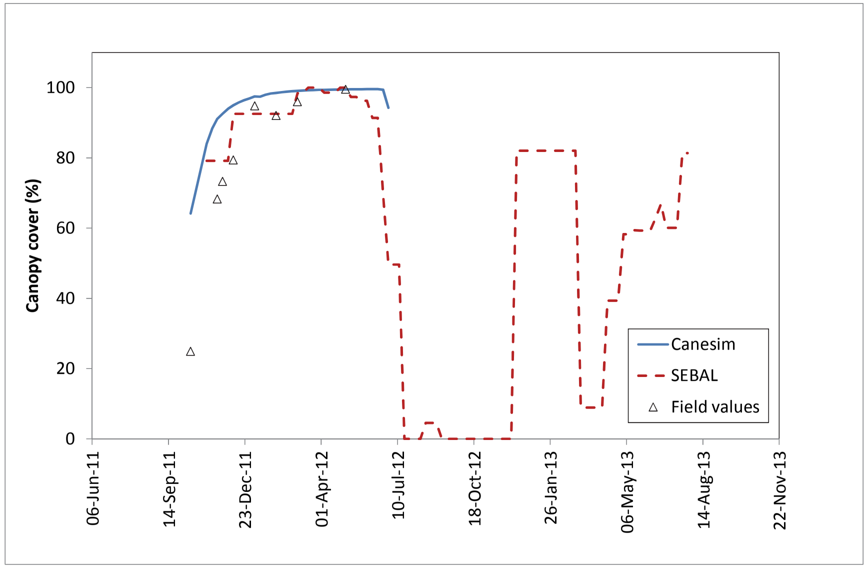
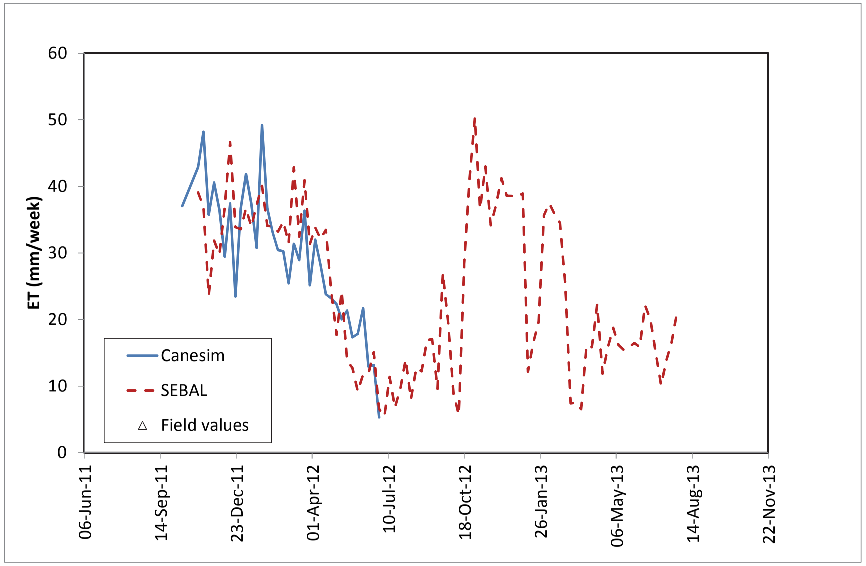
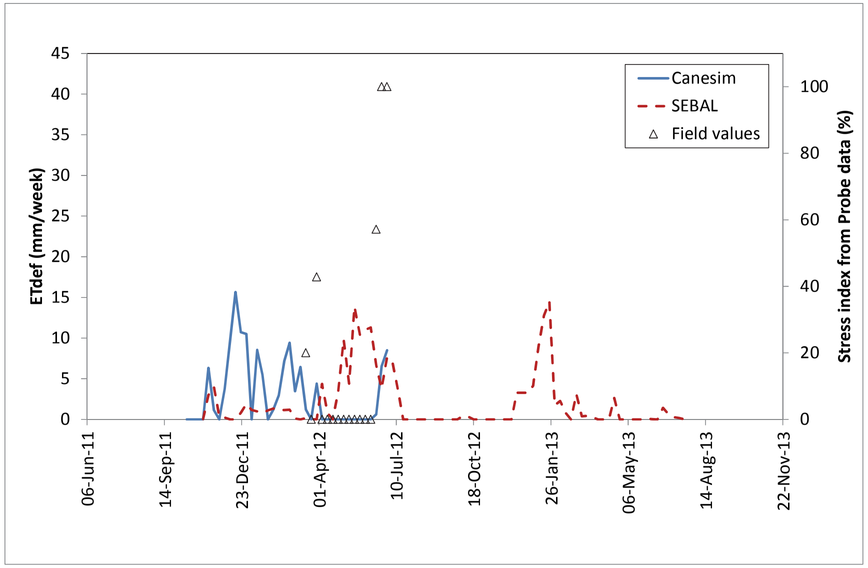
14-Aug-13
22-Nov-13

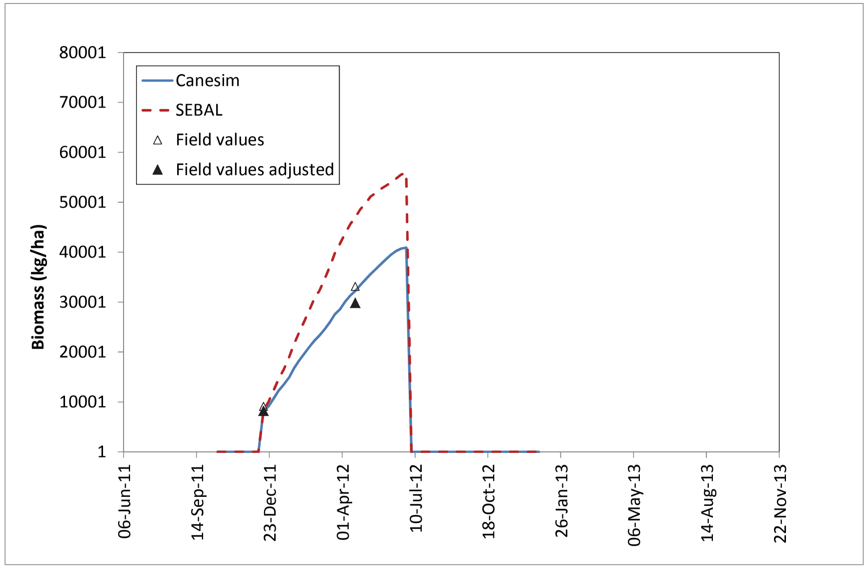

Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

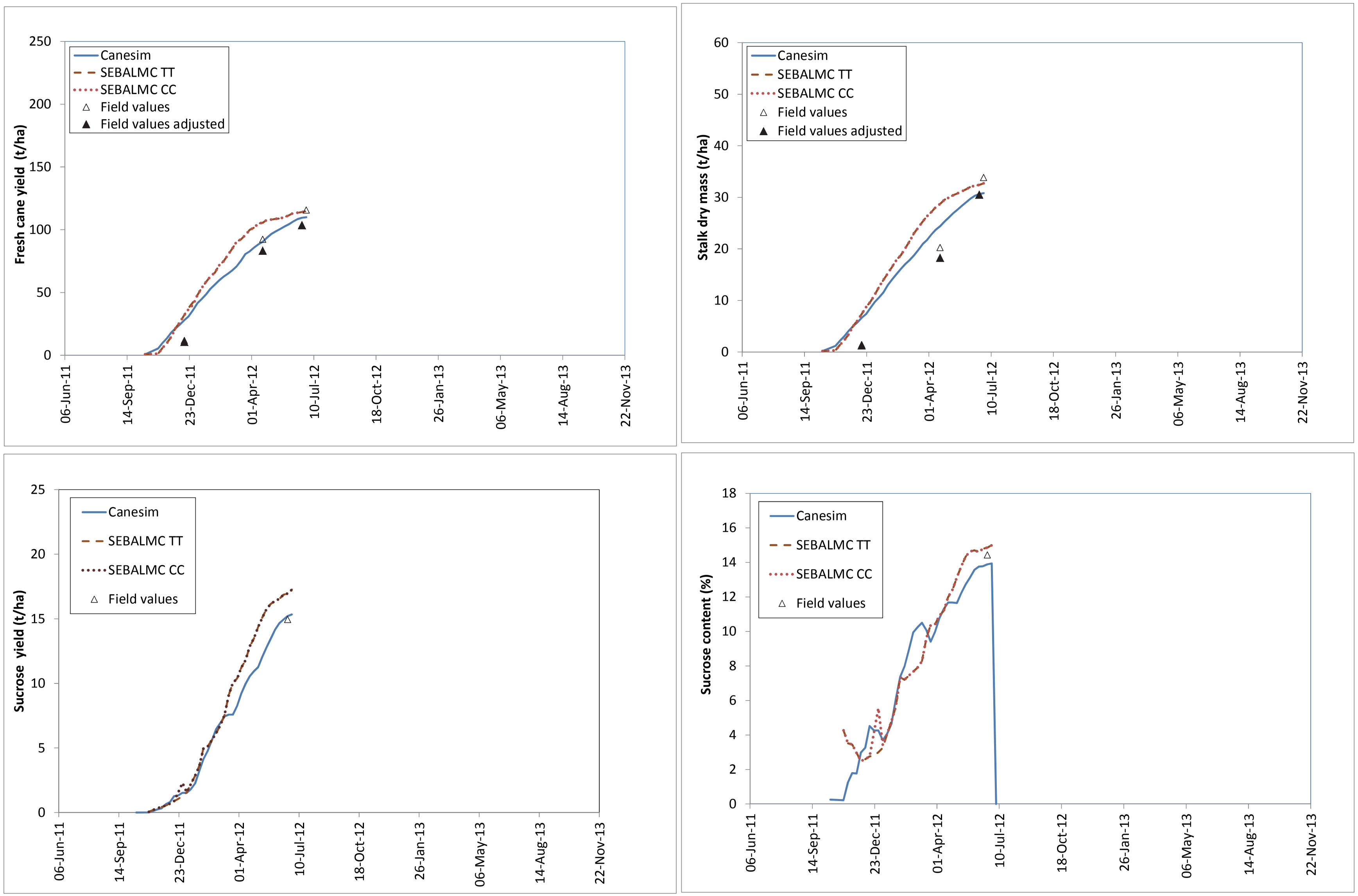
Farm F, Field G7



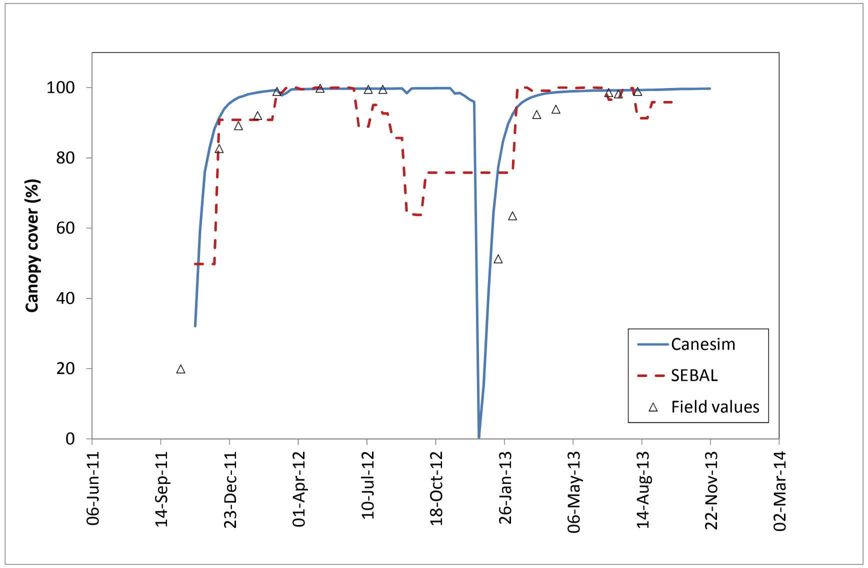


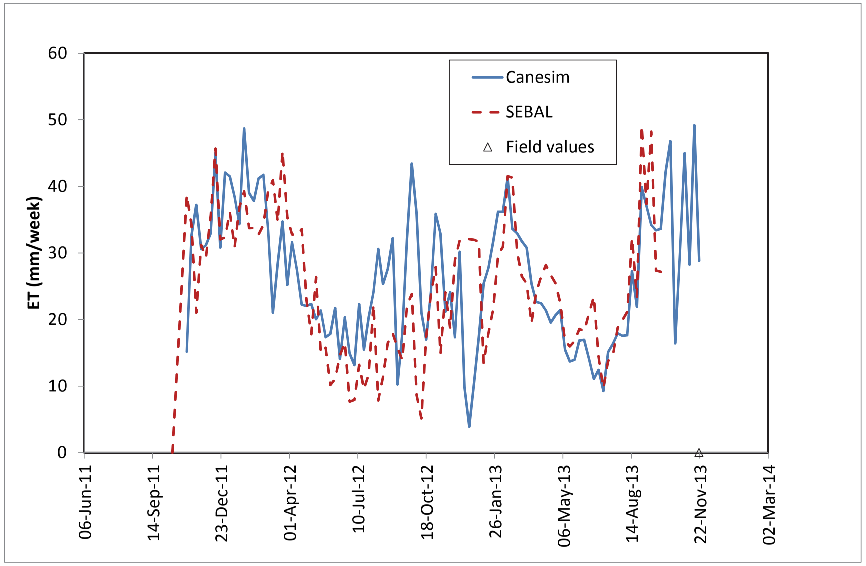


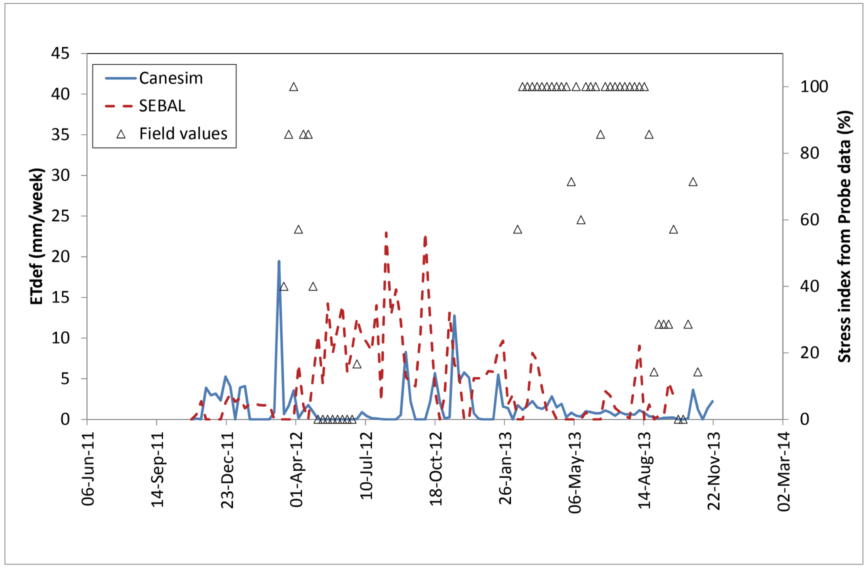


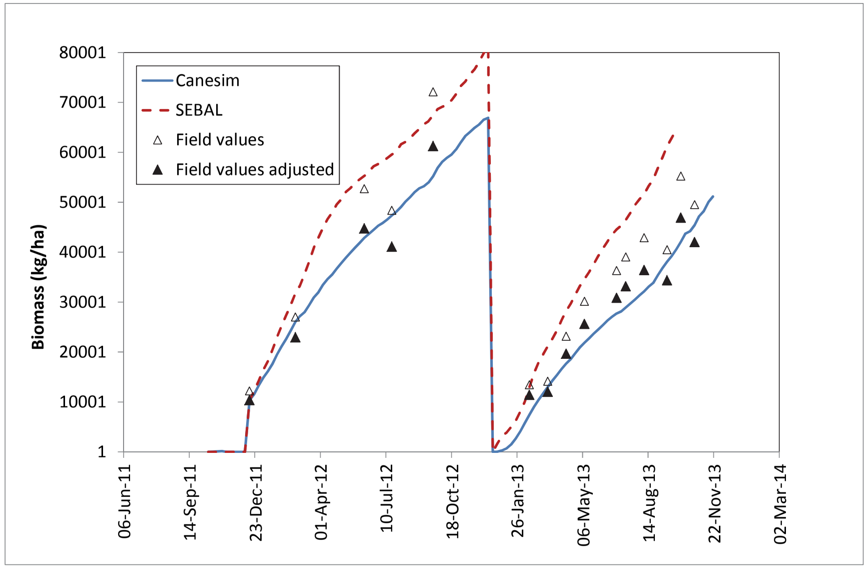

Fresh cane yield (t/ha)
Stalk dry mass (t/ha)
Sucrose yield (t/ha)
Sucrose content (%)
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13

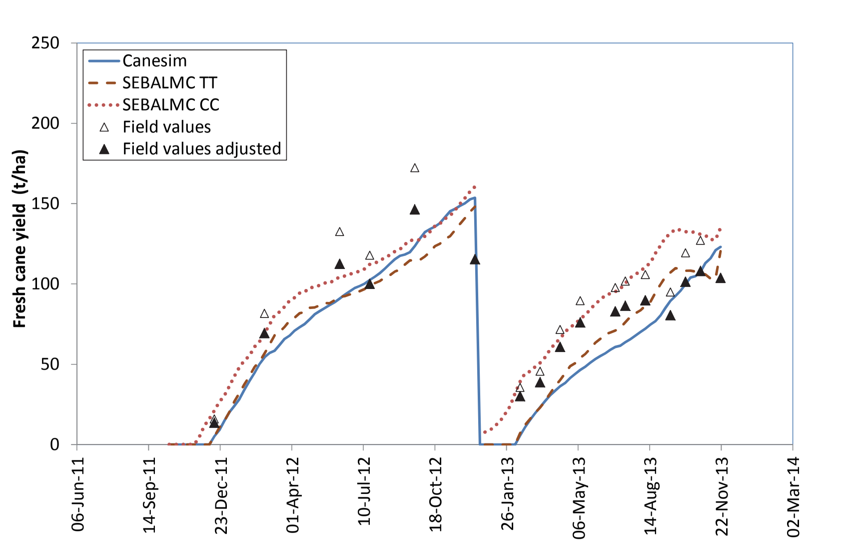
Farm F, Field P4

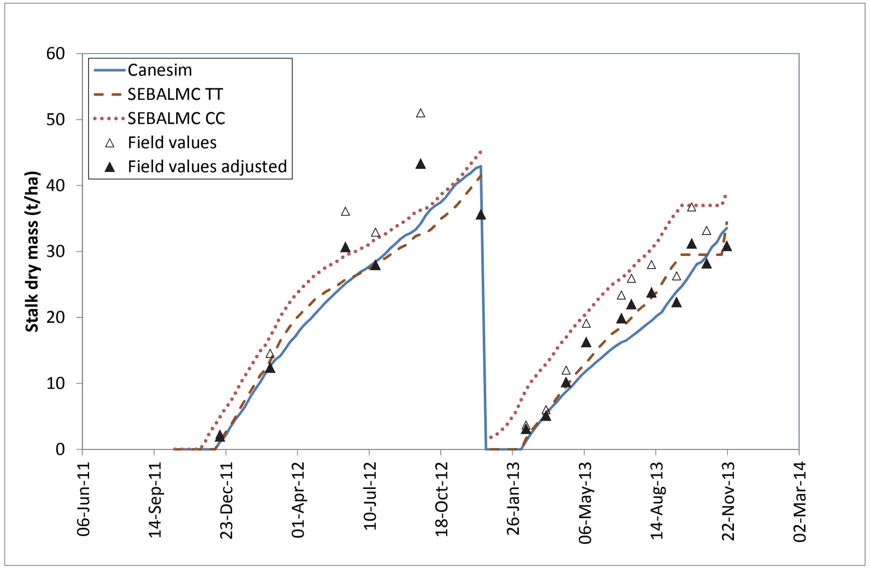


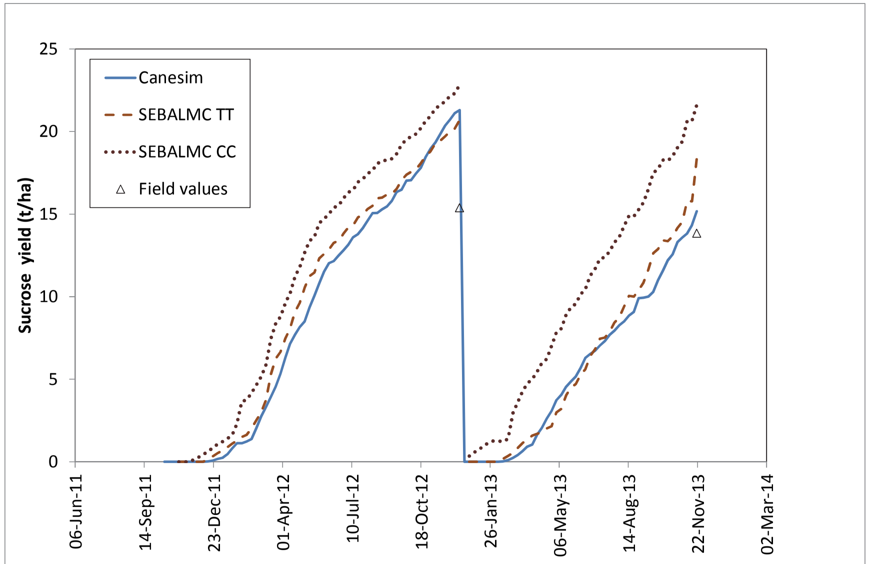


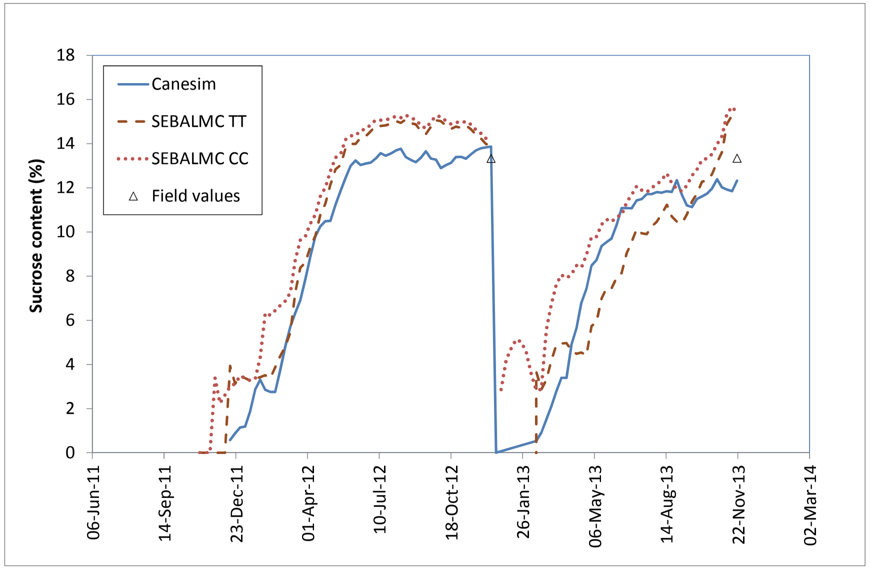





Fresh cane yield (t/ha)
250
200
150
100
50
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14


Stalk dry mass (t/ha)
60
50
40
30
20
10
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
Field values adjusted
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14


Sucrose yield (t/ha)
25
20
15
10
5
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14


Sucrose content (%)
18
16
14
12
10
8
6
4
2
0
Canesim
SEBALMC TT
SEBALMC CC
Field values
06-Jun-11
14-Sep-11
23-Dec-11
01-Apr-12
10-Jul-12
18-Oct-12
26-Jan-13
06-May-13
14-Aug-13
22-Nov-13
02-Mar-14

APPENDIX III: REVIEWING IRRIGATION PRACTICES AND AGRONOMIC PERFORMANCE WITH THE INTEGRATED SYSTEM

REVIEWING IRRIGATION PRACTICES AND AGRONOMIC PERFORMANCE WITH THE INTEGRATED SYSTEM

The potential value of integrating soil water monitoring data with weather-based simulations was demonstrated by inferring the agronomic performance, including the quality of irrigation management, for the different fields by comparing simulated yields using optimal irrigation (Y_{opt}), yields from ASWC corrected simulations (Y_{swc}) and actual yields (Y_{obs}). Criteria for inferring agronomic performance are given in Table AIII.1.

Table AIII.1.Knowledge gained by comparing yields from various simulations. Y_{opt} is the simulated yield using an optimal irrigation schedule; Y_{swc} is the yield from a simulation based on observed soil water records; and Y_{obs} is the actual yield achieved.

Comparison	Deduction
$Y_{obs} > 0.85\ Y_{opt}$	Good irrigation[1], good husbandry
$Y_{obs} < 0.85\ Y_{opt}$	Crop underperformance due to one or more limiting factors
$Y_{swc} > 0.85\ Y_{opt}$	Good irrigation[1]
$Y_{swc} < 0.85\ Y_{opt}$	Under irrigation caused preventable drought stress
$Y_{obs} > 0.85\ Y_{swc}$	Good husbandry
$Y_{obs} < 0.85\ Y_{swc}$	Suboptimal husbandry

[1] – Irrigation practices were evaluated given the limitations of the existing irrigation system

The extent of water stress (drought stress and waterlogging) experienced is also an indication of the appropriateness of irrigation practices. Drought stress days were defined as days when ASWC was less than 40% of TAM, excluding the last 30 days of the season (when irrigations are typically intentionally withheld to promote sucrose accumulation). Water logged days was defined as days when ASWC was greater than 110% of TAM. The CaneSim® model assumes that drought stress occurs when ASWC is below 50% of TAM, and that waterlogging occurs when ASWC exceeds 100% of TAM. Thresholds of 40% and 110% of TAM were chosen in order to exclude days with slight drought and waterlogging stress. When the number of stress days exceeded 30, this was considered to have had a significant impact on yield.

The analysis suggest that 2012 yields were limited well below potential for fields 8A, 8C, 17, 3B and 7, because Y_{obs} was less than 85% of Y_{opt}. Insufficient irrigation and preventable drought stress were inferred for fields 8C (excessive drying off identified) and 17 (irrigation system did not operate for long periods) as shown in Table AIII.2. Fields G7 seemingly also experienced some drought stress as shown in Table AIII.2. This was not reflected in the ratio of Y_{swc} to Y_{opt} because of limited SWI data.

For fields where Y_{obs} was less than 85% of $Y_{swc,}$ that was taken as an indication of the presence of yield limiting factors other than insufficient irrigation, for example poor crop stand, weed competition, nutrient deficiency or pest and disease damage. This seemed to be the case in 2012 for fields 8A, 8C, 3B and 7 (poor crop stand was observed in this field) but this needs to be verified through field visits. Water logging may have been a problem on fields 8C, G1, and 70, 81 as indicated by high numbers of water logged days (Table AIII.2).

In 2013 yield were limited below potential for fields 8C, P4 and 3B (Y_{obs} < 85% of Y_{opt}) (Table AIII.3). For all three fields the presence of limiting factors other than irrigation was identified as a contributing cause, based on the fact that Yobs was less than 85% of Yswc. All three fields also experience periodic water logging, while field 3B had extended period of drought stress.

Table AIII.2.Simulated yields for the 2011-2012 growing season using optimal irrigation (Y_{opt}), observed yields (Y_{obs}) and yields using ASWC corrected simulations (Y_{swc}) expressed as percentages of the $Y_{opt;}$ the number of drought stress days (ASWC<40%TAM, excluding the last 30 days when crops are typically intentionally stressed to prepare the field for harvesting); the number of water logged stress days (ASWC>110%TAM); and the percentage of days of the growing season for which soil water status data was available (SWI data) for each field. Field P4 were not analysed due to too little ASWC data.

Farm code	Field Name	Y_{Opt} (t/ha)	Y_{obs} / Y_{opt} (%)	Y_{swc} / Y_{opt} (%)	Y_{obs} / Y_{swc} (%)	Stress days (drought)	Stress days (water logged)	SWI data availability (%)	Main conclusion from analysis[1]
A	8A	116	76	95	81	23	13	59	Good irrigation, suboptimal husbandry
A	8C	116	71	86	83	56	44	69	Good irrigation, suboptimal husbandry, some water logging. Excessive drying off.
B	17	89	78	62	126	187	17	73	Under irrigation, good husbandry, prolonged drought stress.
C	G1	126	85	96	89	0	30	57	Good irrigation, good husbandry, some water logging.
C	G4	123	102	97	105	0	23	25	Good irrigation, good husbandry.
C	G7	113	92	97	94	45	818	33	Good irrigation, good husbandry, drought stress due to system limitations.
D	3B	135	59	93	64	2	10	55	Good irrigation, suboptimal husbandry.
D	7	120	67	91	73	27	24	63	Good irrigation, suboptimal husbandry
E	12	101	92	97	104	40	4	61	Good irrigation, good husbandry, some drought stress.
F	70	123	92	96	97	5	77	61	Good irrigation, good husbandry, water logging.
F	72	153	93	100	93	8	23	83	Good irrigation, good husbandry.
F	81	130	86	93	92	14	35	88	Good irrigation, good husbandry, some water logging.

[1] – "Good irrigation" means good scheduling given the limitations of the exiting irrigation system.

Table AIII.3.Simulated yields for the 2012-2013 growing season from optimal irrigation (Y_{opt}), observed yields (Y_{obs}) and yields using ASWC corrected simulations (Y_{swc}) expressed as percentages of the $Y_{opt;}$ the number of drought stress days (ASWC<40%TAM, excluding the last 30 days when crops are typically intentionally stressed to prepare the field for harvesting); the number of water logged stress days (ASWC>110%TAM); and the percentage of days of the growing season for which soil water status data was available (SWI data) for each field.

Farm code	Field Name	Y_{Opt} (t/ha)	Y_{obs} / Y_{opt} (%)	Y_{swc} / Y_{opt} (%)	Y_{obs} / Y_{swc} (%)	Stress days (drought)	Stress days (water logged)	SWI data availability (%)	Main conclusion from analysis[1]
A	8A	115	86	98	88	13	63	63	Good irrigation, good husbandry, some water logging.
A	8C	115	82	98	84	8	30	87	Good irrigation, suboptimal husbandry.
B	17	112	97	65	150	141	69	54	Under irrigation, good husbandry, prolonged drought stress, some water logging.
C	G1	123	90	91	99	83	16	71	Good irrigation, good husbandry, a long period of drought stress at the start of crop.
C	G4	121	114	100	114	48	24	75	Good irrigation, good husbandry.
C	P4	128	81	96	84	0	32	75	Good irrigation, suboptimal husbandry, water logging.
D	3B	160	61	79	78	127	58	72	Under irrigation, suboptimal husbandry, excessive drying off, water logging.
E	12	94	107	89	121	48	11	72	Good irrigation, good husbandry, mild drought stresses.
F	70	110	105	111	95	132	15	92	Good irrigation, good husbandry, long period of drought stress at start of crop.
F	72	111	105	99	107	0	30	92	Good irrigation, good husbandry.
F	81	128	95	100	95	7	21	92	Good irrigation, good husbandry.

[1] – "Good irrigation" means good scheduling given the limitations of the exiting irrigation system.

Soil water status data from capacitance soil water sensors were successfully integrated into the weather-based MyCaneSim® simulation system. Layered soil water status data were converted to root zone available soil water content using a linear scaling formula. Field specific calibration coefficients were derived from drainage and extraction patterns. The study showed that it is difficult to infer historic irrigation events reliably from soil water status records and that measurement with flow meters or rain gauges are needed for accurate records.

Useful knowledge regarding the irrigation management and agronomic performance were gained by analysing simulation outputs and observed cane yields. Evaluations indicated that:

- Observed yields were well below simulated potential yields for five out of 12 fields in 2012 and in three out of 11 fields in 2013. In two of these fields under-irrigation was identified as a major yield limiting factor.

- Observed yields were well below simulated yields based on a ASWC corrected water balance in four fields, suggesting that yield limiting factors other than suboptimal irrigation could have been present. These fields could be targeted for closer inspection to identify and remedy agronomic problems.

- Significant water logging was evident from soil water data in four fields, while periods of preventable drought stress were evident in three fields. This information should help farmers adjust their practices to achieve higher yields through more effective irrigation.

The integrated MyCaneSim® system provides enhanced support for irrigation water management for sugarcane production. Farmers and extension specialists can understand the impact of irrigation practices on the soil water regime and its impact on crop growth and yield. This is a good basis for making adjustments to irrigation practices and for benchmarking crop performance and water use efficiency against potential. The system can also be used to support scheduling decisions based on its forecasts of soil and crop water status and the next irrigation date.

APPENDIX IV: VALIDATION OF FIELD ESTIMATES OF THE SURFACE ENERGY BALANCE AND DAILY ET IN MAIZE

VALIDATION OF FIELD ESTIMATES OF THE SURFACE ENERGY BALANCE AND DAILY ET IN MAIZE

In the section below the SEBAL energy balance and evapotranspiration data estimated for the maize fields are compared with that measured. SEBAL solves the surface energy balance at the time of satellite overpass (Table AIV.1) and integrates the energy fluxes to provide estimates of daily and weekly ET using the evaporative fraction (EF) data. Evaporative fraction can be defined of the latent energy flux (LE) fraction of the available energy (R_n-G). In this section the energy balance and ET data from the maize field is compared on 15 days over the season.

Table AIV.1. Dates and times of a selection of thermal images used in the instantaneous modelling at the maize site

Site	Date	Time	Site	Date	Time	Site	Date	Time
Taai04	25-Jan-13	1330	Taai04	02-Mar-13	1400	Taai04	11-Apr-13	1500
Taai04	26-Jan-13	1430	Taai04	09-Mar-13	1500	Taai04	22-Apr-13	1400
Taai04	05-Feb-13	1500	Taai04	17-Mar-13	1400	Taai04	28-Apr-13	1400
Taai04	16-Feb-13	1500	Taai04	20-Mar-13	1500	Taai04	06-May-13	1300
Taai04	23-Feb-13	1400	Taai04	05-Apr-13	1500	Taai04	12-May-13	1500

The SEBAL data used in this part of the report represents the average for the entire field within which the measurements were performed. The spatial data for the maize field do show some heterogeneity across the field (Figure AIV.1), at a specific time.

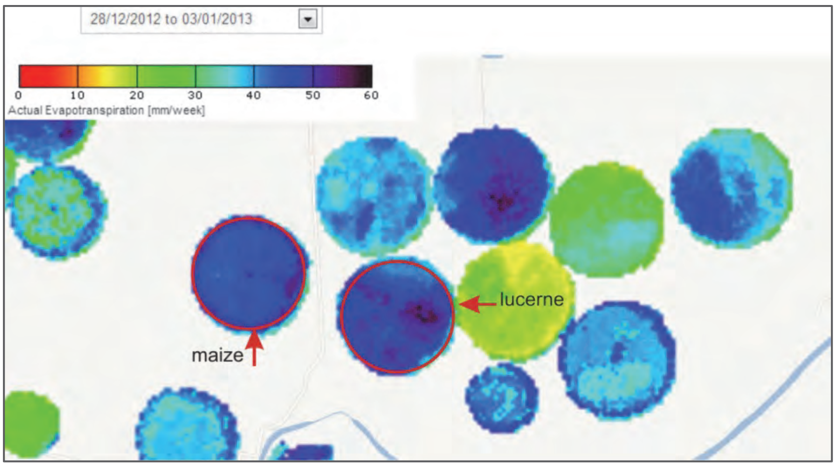


Figure AIV.1. Spatial image of weekly evapotranspiration (week ending 3 January 2013) for the maize and lucerne fields showing the spatial variation in the fields

Instantaneous energy balance data comparison

Net radiation (R_n) measured and modeled with SEBAL at the maize site show a decrease in the values from January to May 2013 (Figure AIV.2). Good agreement exists between the measured and SEBAL data, with SEBAL significantly explaining more than 99 % of the variation in the measured R_n ($p<0.05$; $R^2=0.99$) (Table AIV.2). The soil heat flux density (G) measured and estimated showed differences and agreements. SEBAL explained 74 % of the variation in the measured G in the maize field ($p<0.05$) (Table AIV.2).

At the maize field, the sensible heat flux (H) measured consistently exceeded that estimated with SEBAL. The SEBAL estimates explained 88 % of the variation in the measured H at the maize field ($p<0.05$) (Table AIV.2). The underestimation in the SEBAL H estimates were substantial (0.45) (slope=1.07) (Table AIV.2). The latent energy flux estimates (LE) again agreed better than the H estimates, with the SEBAL estimates explaining more than 90 % of the variation in the measured LE at the maize field ($R^2=0.9$ and $R^2=0.92$ respectively)($p<0.05$) (Table AIV.2).

The evaporative fraction data showed scatter: the SEBAL estimates explained more than 95% of the variation in the measured data ($R^2=0.95$) (Table AIV.2). The SEBAL and measured EF data followed a similar trend throughout the maize growing season.

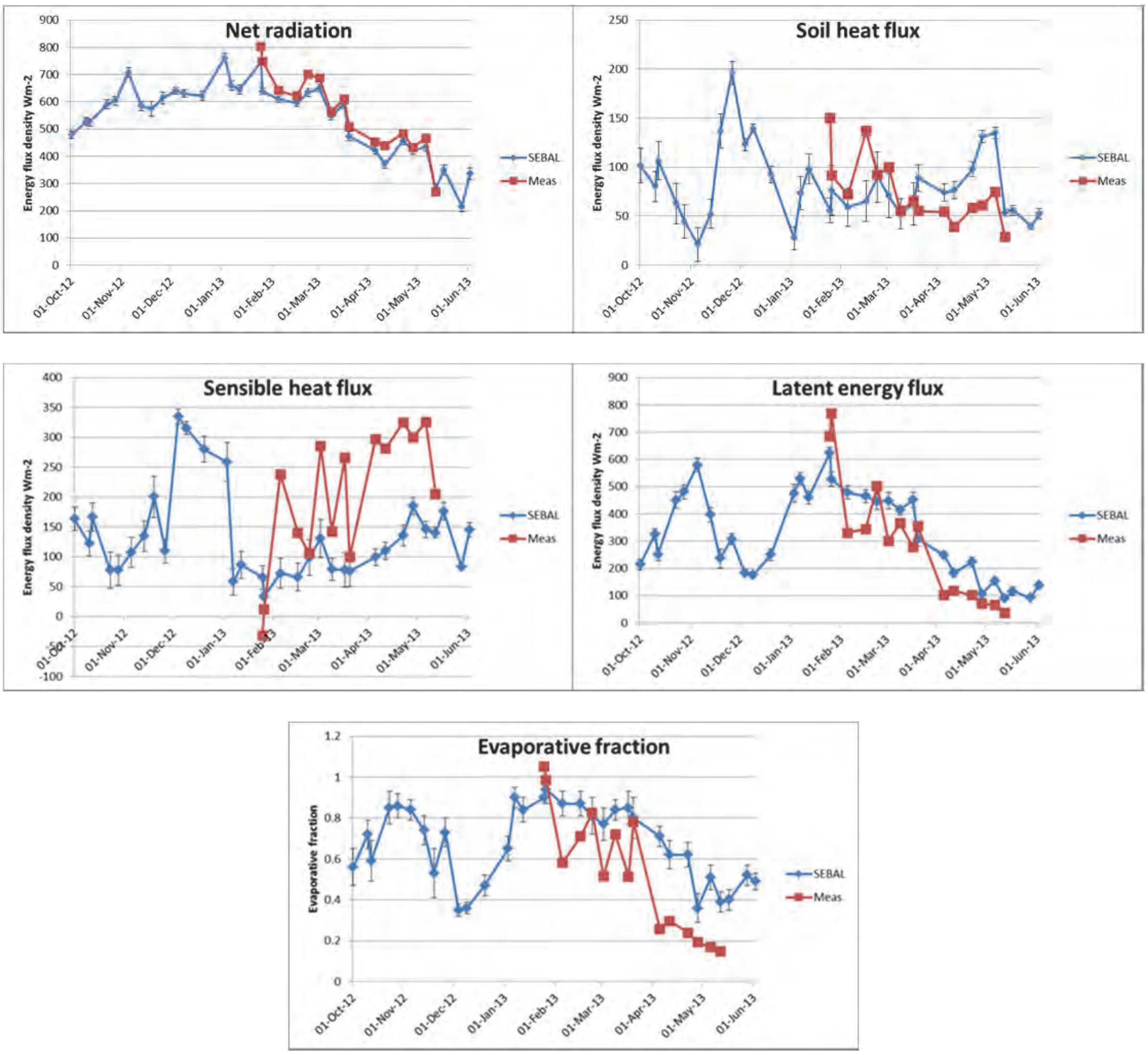


Figure AIV.2. Comparisons of instantaneous estimates of net radiation (R_n), soil heat flux (G), sensible heat flux density, latent energy flux density (LE) and evaporative fraction (EF) with SEBAL with measured data at the maize site

Table AIV.2. Regression statistics (measured *vs*. SEBAL) estimated for energy balance parameters estimated at the time of satellite overpass and for that day and also for daily ET at the irrigated maize site

Measured *vs*. SEBAL : Maize										
Regression stats	Instantaneous					Day				
	Rn_i	G_i	H_i	EF_i	LE_i	Rn_24	G_24	H_24	LE_24	ET
Multiple R	0.999	0.859	0.940	0.948	0.950	0.997	0.714	0.893	0.970	0.974
R Square	0.998	0.738	0.884	0.899	0.903	0.994	0.510	0.798	0.941	0.948
Adjusted R Square	0.927	0.666	0.813	0.827	0.832	0.922	0.438	0.727	0.870	0.877
Standard Error	24.605	44.044	38.133	0.245	122.355	13.507	2.682	16.922	34.461	1.144
Observations	15	15	15	15	15	15	15	15	15	15
Significance F (*p*)	3.21E-19	2.87046E-05	1.23E-07	4.99E-08	3.68E-08	5.70134E-16	0.002151005	4.87051E-06	1.41163E-09	6.0328E-10
Intercept	0	0	0	0	0	0	0	0	0	0
X Variable 1	0.93	0.866	0.45	1.16	0.99	1.055	-0.437	0.549	0.987	0.990

Daily energy balance data comparison

The daily SEBAL estimates of the energy balance and the evaporative fraction was compared to that observed at the maize field for the days that satellite data was available for (Table AIV.1).

Data comparisons show similar trends to that found for the instantaneous data. Net radiation estimates measured and modeled were very similar (Figure AIV.3). The SEBAL estimates explained more than 99% of the variation in the daily average measured R_n (R^2=0.9) (Table AIV.2). The Sensible heat flux density showed more scatter, but still the SEBAL estimates explained more than 73 % of the variation in the daily average measured H (R^2=0.89) (Table AIV.2). The measured and the SEBAL estimates of EF and LE similarly showed good agreement in the daily estimates (Figure AIV.3).

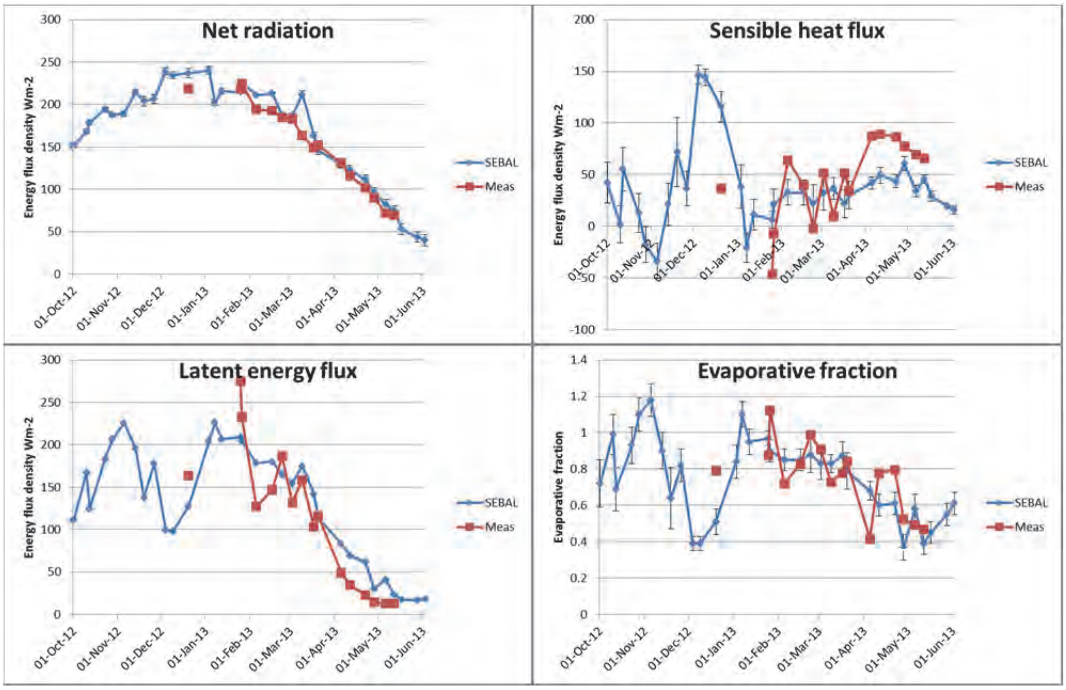


Figure AIV.3. Comparisons of daily estimates of net radiation (R_n), sensible heat flux density, latent energy flux density (LE) and evaporative fraction (EF) with SEBAL with measured data from the maize field

Daily evapotranspiration comparison

The daily SEBAL ET estimates were compared to the measured or observed ET. The daily ET estimates showed a good agreement (Figure AIV.4), with the SEBAL ET estimates explaining > 90 % of the variation in the measured ET (R^2=0.97) (Table AIV.2). The slope of the linear regressions for the maize field was 0.99 (Table AIV.2).

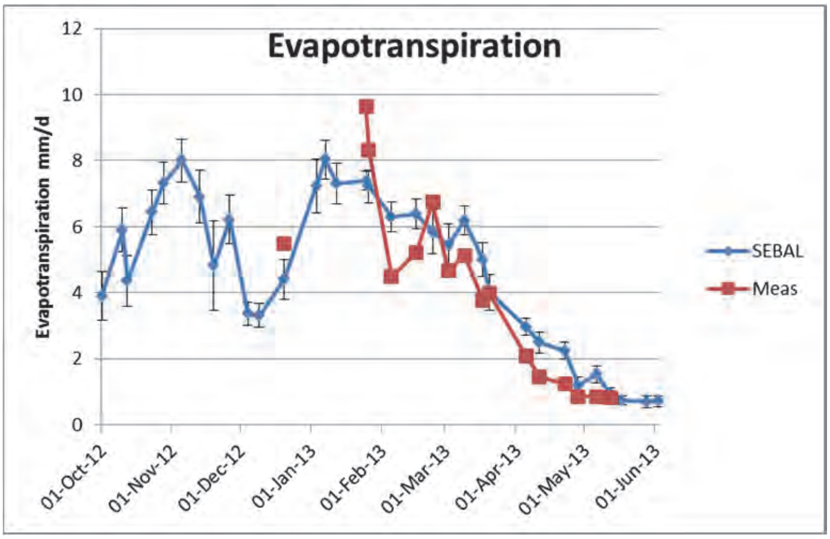


Figure AIV.4. Daily evapotranspiration observed and estimated with SEBAL at the maize field

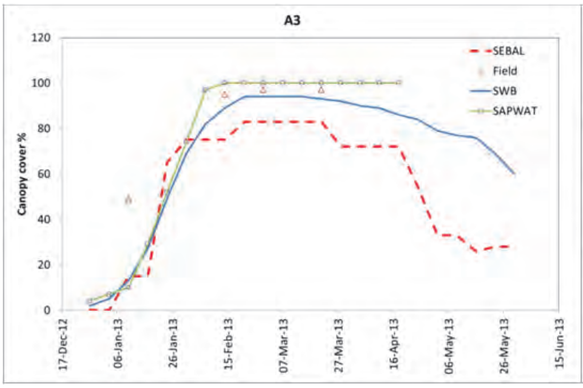
APPENDIX V: ADDITIONAL COMPARATIVE DATA SETS FOR THE MAIZE FIELDS STUDIED

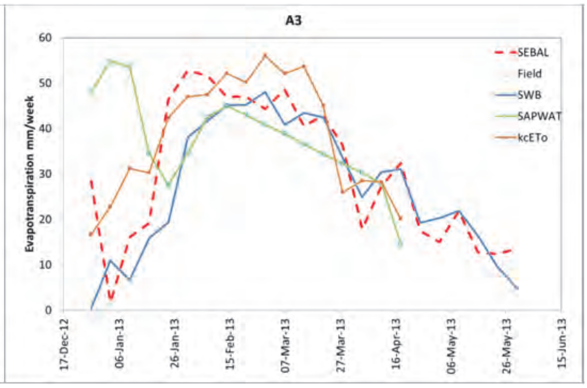
ADDITIONAL VALIDATION DATA FROM MAIZE FIELDS STUDIED

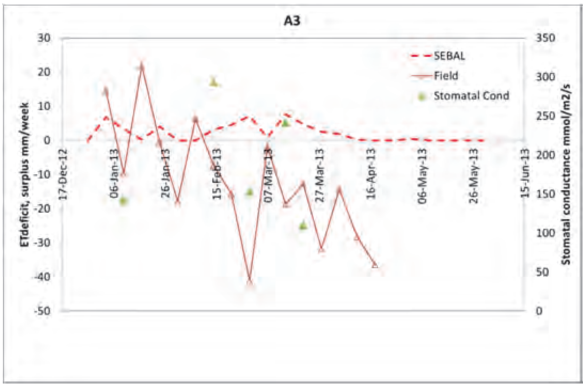
Below more data from the maize fields are shown. The observations (field measurements) of canopy cover (CC), evapotranspiration (ET), evapotranspiration deficit (ET_{def}) and areal dry matter (ADM) observed are compared to estimates from SEBAL, SWB and SAPWAT (where data was available). Yield estimates from SWB and field observations representing grain plus cob mass are also shown together with average SEBAL and combine harvester estimates of grain mass only.

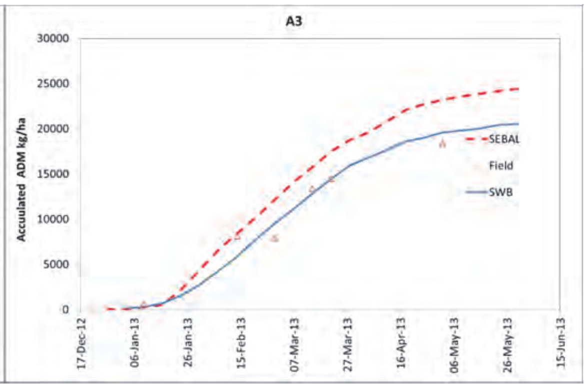
The results shown below are in addition to that shown in Chapter 5.

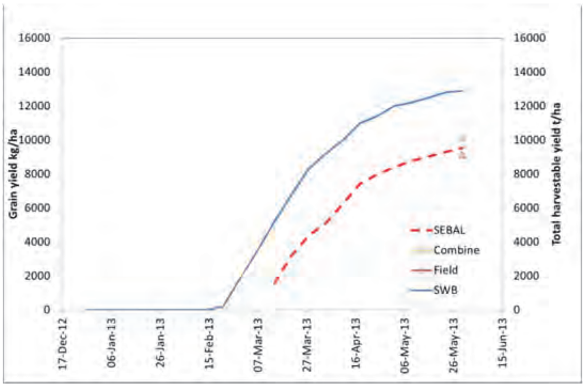
Field A3



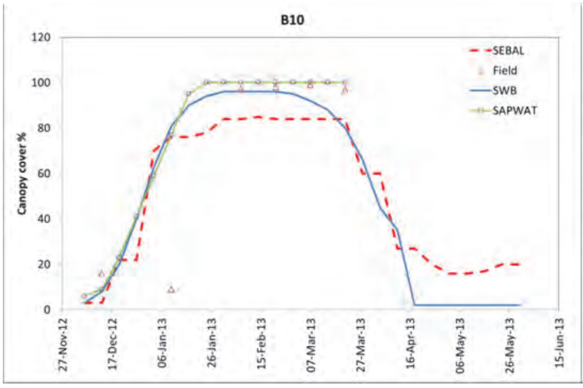


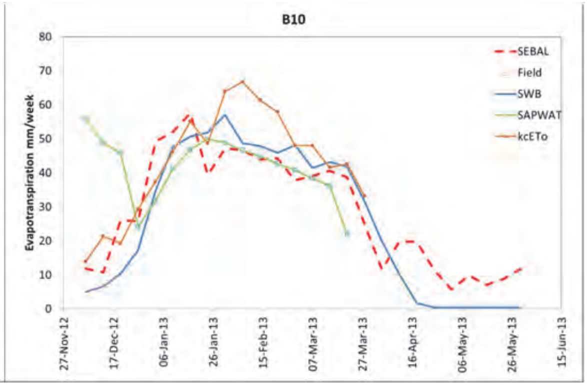






Field B10


B10
SEBAL
Field
SWB
SAPWAT
Canopy cover %
120
100
80
60
40
20
0
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13


B10
SEBAL
Field
SWB
SAPWAT
kcETo
Evapotranspiration mm/week
80
70
60
50
40
30
20
10
0
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
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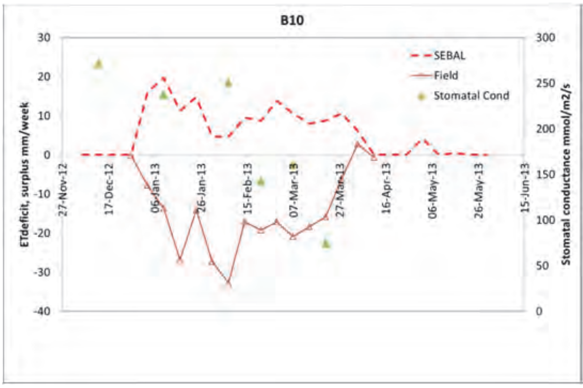
06-May-13
26-May-13
15-Jun-13


B10
SEBAL
Field
Stomatal Cond
ETdeficit, surplus mm/week
Stomatal conductance mmol/m2/s
30
20
10
0
-10
-20
-30
-40
300
250
200
150
100
50
0
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
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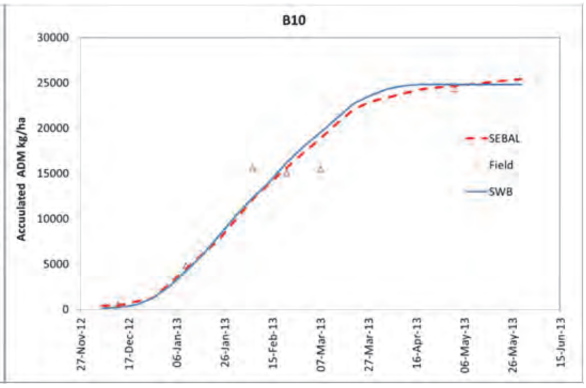
26-May-13
15-Jun-13


B10
SEBAL
Field
SWB
Accuulated ADM kg/ha
30000
25000
20000
15000
10000
5000
0
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
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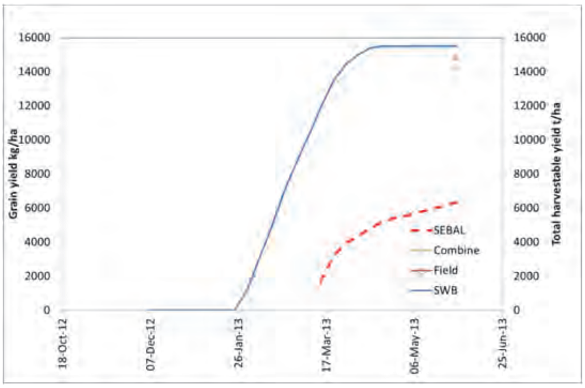
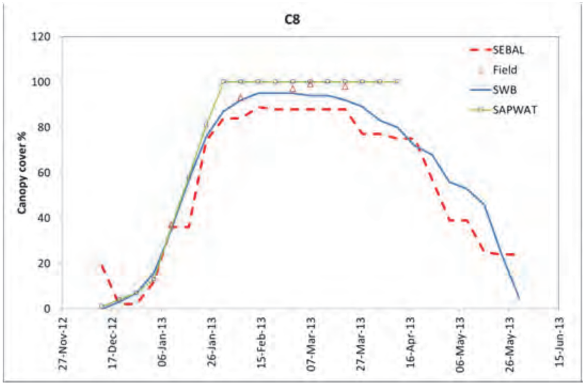
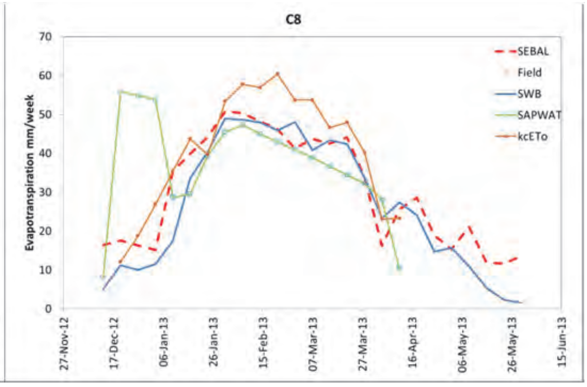
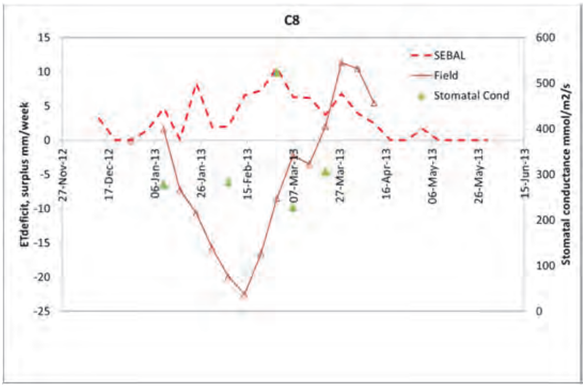
16-Apr-13
06-May-13
26-May-13
15-Jun-13

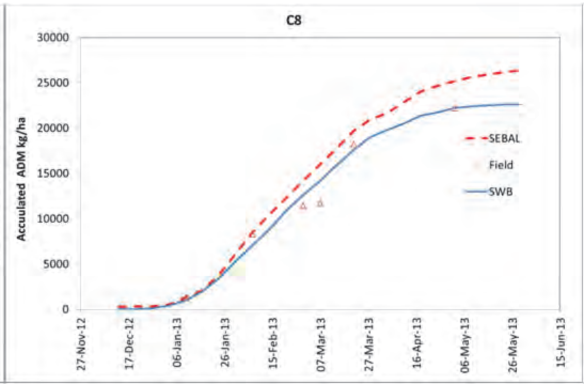

SEBAL
Combine
Field
SWB
Grain yield kg/ha
Total harvestable yield t/ha
16000
14000
12000
10000
8000
6000
4000
2000
0
18-Oct-12
07-Dec-12
26-Jan-13
17-Mar-13
06-May-13
25-Jun-13

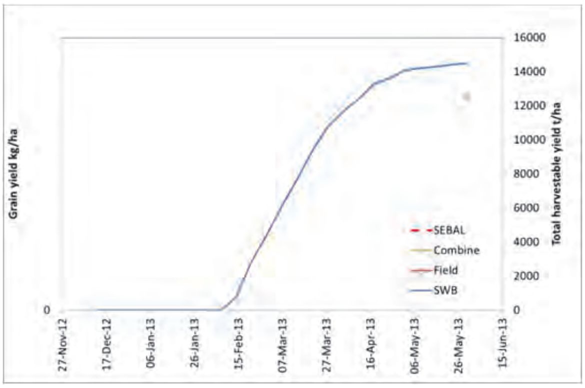
Field C8


C8
Canopy cover %
SEBAL
Field
SWB
SAPWAT

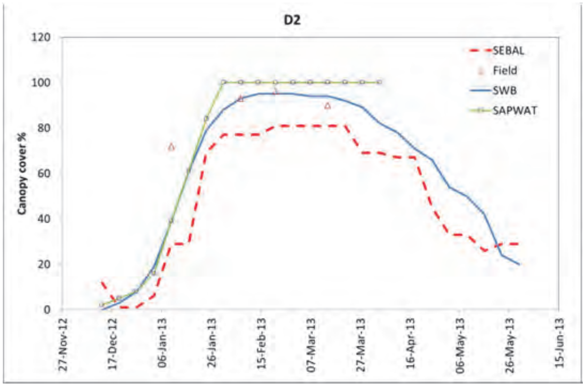

C8
Evapotranspiration mm/week
SEBAL
Field
SWB
SAPWAT
kcETo

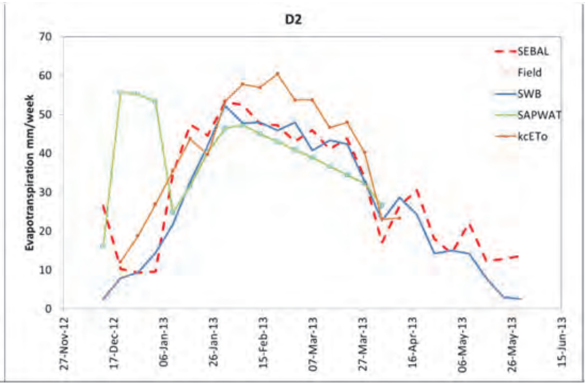

C8
ETdeficit, surplus mm/week
Stomatal conductance mmol/m2/s
SEBAL
Field
Stomatal Cond


C8
Acculated ADM kg/ha
SEBAL
Field
SWB


Grain yield kg/ha
Total harvestable yield t/ha
SEBAL
Combine
Field
SWB

Field D2


D2
Canopy cover %
SEBAL
Field
SWB
SAPWAT
0
20
40
60
80
100
120
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13


D2
Evapotranspiration mm/week
SEBAL
Field
SWB
SAPWAT
kcETo
0
10
20
30
40
50
60
70
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
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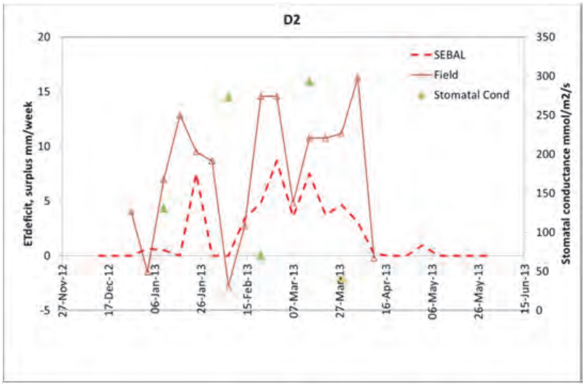
26-May-13
15-Jun-13


D2
ETdeficit, surplus mm/week
Stomatal conductance mmol/m2/s
SEBAL
Field
Stomatal Cond
-5
0
5
10
15
20
0
50
100
150
200
250
300
350
27-Nov-12
17-Dec-12
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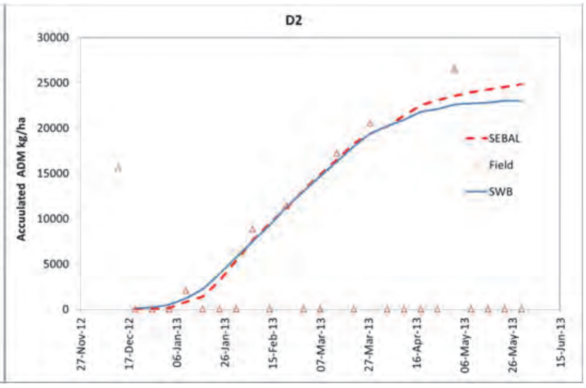
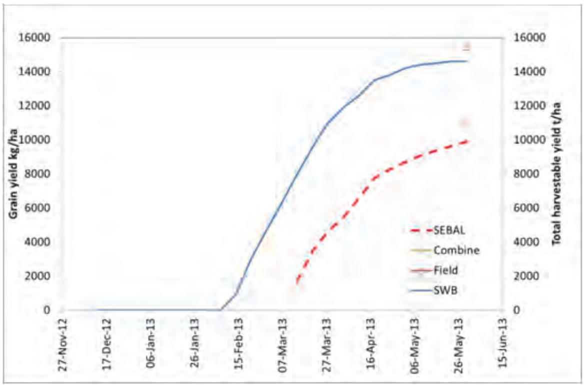
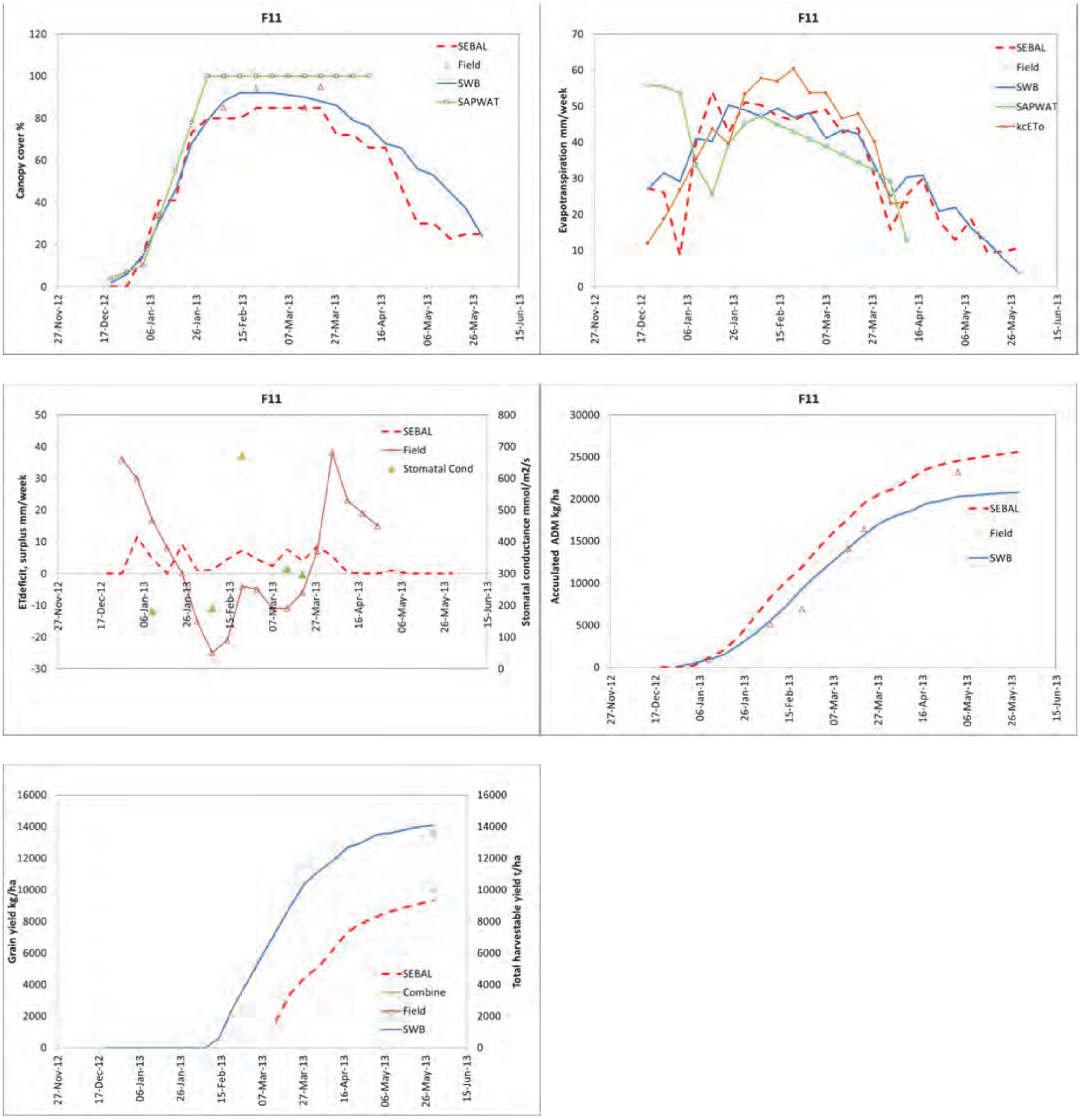
26-May-13
15-Jun-13

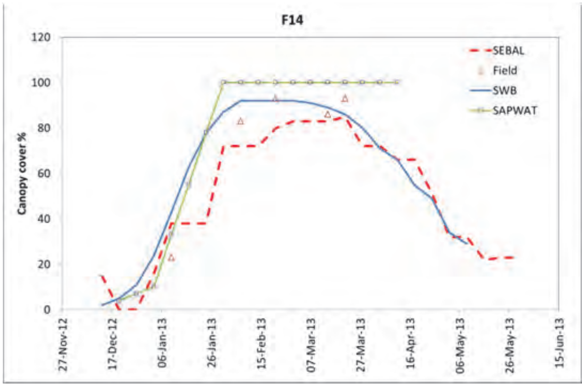

D2
Acculated ADM kg/ha
SEBAL
Field
SWB
0
5000
10000
15000
20000
25000
30000
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13


Grain yield kg/ha
Total harvestable yield t/ha
SEBAL
Combine
Field
SWB
0
2000
4000
6000
8000
10000
12000
14000
16000
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13

Field F11


F11
Canopy cover %
SEBAL
Field
SWB
SAPWAT
F11
Evapotranspiration mm/week
SEBAL
Field
SWB
SAPWAT
kcETo
F11
ETdeficit, surplus mm/week
Stomatal conductance mmol/m2/s
SEBAL
Field
Stomatal Cond
F11
Acculated ADM kg/ha
SEBAL
Field
SWB
Grain yield kg/ha
Total harvestable yield t/ha
SEBAL
Combine
Field
SWB

Field F14


F14
Canopy cover %
SEBAL
Field
SWB
SAPWAT
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
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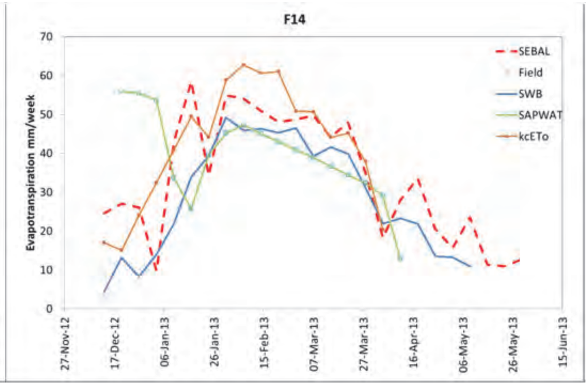
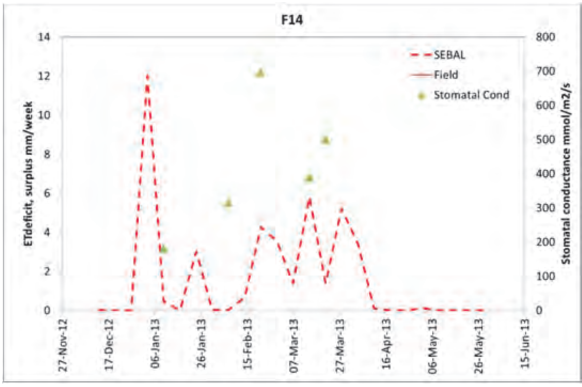
26-May-13
15-Jun-13


F14
Evapotranspiration mm/week
SEBAL
Field
SWB
SAPWAT
kcETo
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13


F14
ETdeficit, surplus mm/week
Stomatal conductance mmol/m2/s
SEBAL
Field
Stomatal Cond
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
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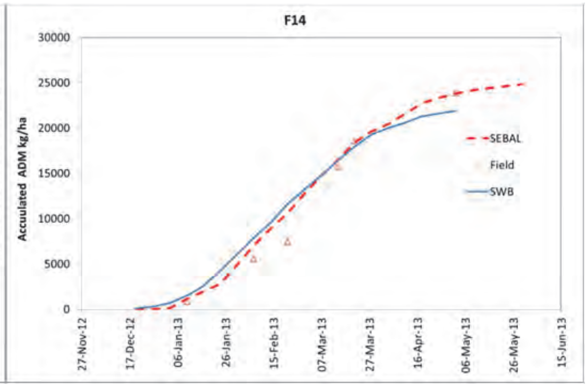
26-May-13
15-Jun-13


F14
Acculated ADM kg/ha
SEBAL
Field
SWB
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
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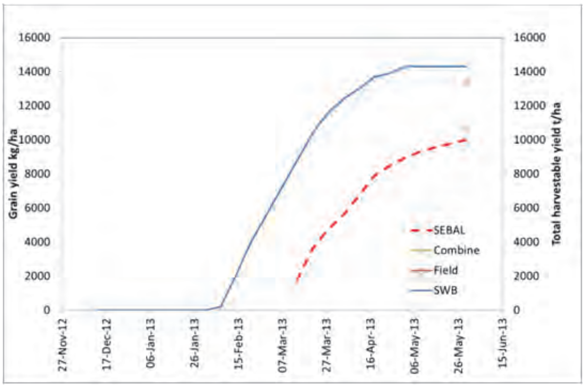
26-May-13
15-Jun-13


Grain yield kg/ha
Total harvestable yield t/ha
SEBAL
Combine
Field
SWB
27-Nov-12
17-Dec-12
06-Jan-13
26-Jan-13
15-Feb-13
07-Mar-13
27-Mar-13
16-Apr-13
06-May-13
26-May-13
15-Jun-13

APPENDIX VI: EXAMPLE REPORT PREPARED BASED ON MYCANESIM® DATA

EXAMPLE REPORT PREPARED BASED ON MYCANESIM® DATA

Double-click on the file below to open

1

OVERVIEW OF FIELDS MONITORED BY SASRI FOR THE 2011/12 AND 2012/13 GROWING SEASONS

Aresti Paraskevopoulos and Abraham Singels
SASRI in collaboration with UKZN and TSB
5 FEBRUARY 2014

This document briefly reviews irrigation practices and its impacts on soil water status and crop growth for the two fields monitored at Allan Ridge Trust in 2011 to 2013 for the SEBAL project.

Login at portal.sasa.org.za to view simulations: login: 901008C; password: Dane. For help using the site, please contact Aresti Paraskevopoulos.

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Cellular :	: +27 79 648 8941	**Cell**	: +27 83 655 4092
E-mail	: aresti.paraskevopoulos@sugar.org.za	**E-mail**	: abraham.singels@sugar.org.za
Website	: http://www.sasa.org.za	**Website**	: http://www.sasa.org.za

APPENDIX VII: EXAMPLES OF SUGARCANELOOK DATA USED BY TSB (PROVIDED BY DR PIETER CRONJE, TSB)

Double click on file to open

Summary- Production Statistics: Libuyile- 2009-2012

CPR Cronjé, TSB

The following report is based on the Cane-Pro dataset and is subject to the accuracy of the data set.

Table 1: Libuyile- Historic production data: 2009-2012

Harvest Year	Days Growth	TPH	Sucrose %	Fibre %	Purity %	Rel RV %	RV %	Moisture %	Non-sucrose %	Ton/Rv/Ha/Ann	Ton/RRV/Ha/Ann
2009	360.72	111.79	14.41	13.74	85.54	13.27	13.18	69.44	2.53	14.86	15.02
2010	373.46	115.44	14.19	13.27	86.38	12.81	13.02	70.31	2.41	14.73	14.48
2011	405.43	127.52	13.53	13.36	84.47	12.26	12.22	70.70	2.56	14.22	14.24
2012	374.54	121.33	13.88	13.40	84.44	12.69	12.61	70.47	2.44	14.93	15.03

When compared to other major production units in the Komati area, the Libuyile group of farms are among the top four growers in the area since 2009. The group often carries some of the highest average tonnage per unit area, and in the top 4 when quality data is concidered. In terms of "days growth", the group often carries the longest growth periods in the group.

Table 2: Top 4 Komati Performers- Comparative Data 2009-2012

Farm	Harvest Year	Days Growth	Area To Harvest	Total Tons	TPH	Sucrose %	Fibre %	Purity %	Rel RV %	RV %	Moisture %	Non-sucrose %	Ton/Rv/Ha/Ann	Ton/RRV/Ha/Ann
Crookes Bros	2009	367.23	2141.21	228657.00	105.35	14.56	13.35	86.07	13.41	13.37	69.79	2.45	14.04	14.11
Crookes Bros	2010	358.71	2078.50	219722.92	104.43	14.30	13.52	87.25	13.17	13.18	70.24	2.23	14.02	14.01
Crookes Bros	2011	377.29	2155.05	241289.81	108.55	14.22	13.33	86.92	13.02	13.03	70.37	2.26	14.63	14.54
Crookes Bros	2012	365.40	1976.50	223501.09	111.96	13.96	13.58	85.88	12.70	12.76	70.49	2.26	14.30	14.27
Farm	Harvest Year	Days Growth	Area To Harvest	Total Tons	TPH	Sucrose %	Fibre %	Purity %	Rel RV %	RV %	Moisture %	Non-sucrose %	Ton/Rv/Ha/Ann	Ton/RRV/Ha/Ann
Libuyile	2009	360.72	3466.90	384311.40	111.79	14.41	13.74	85.54	13.27	13.18	69.44	2.53	14.86	15.02
Libuyile	2010	373.46	3203.90	363587.98	115.44	14.19	13.27	86.38	12.81	13.02	70.31	2.41	14.73	14.48
Libuyile	2011	405.43	3160.00	381433.81	127.52	13.53	13.36	84.47	12.26	12.22	70.70	2.56	14.22	14.24
Libuyile	2012	374.54	2982.70	337623.44	121.33	13.88	13.40	84.44	12.69	12.61	70.47	2.44	14.93	15.03
Farm	Harvest Year	Days Growth	Area To Harvest	Total Tons	TPH	Sucrose %	Fibre %	Purity %	Rel RV %	RV %	Moisture %	Non-sucrose %	Ton/Rv/Ha/Ann	Ton/RRV/Ha/Ann
Noordgrens	2009	355.45	551.00	75156.00	133.19	13.94	12.25	84.44	12.71	12.68	71.27	2.68	17.50	17.56
Noordgrens	2010	357.54	690.30	87499.60	124.39	13.75	12.70	85.99	12.55	12.60	71.39	2.40	15.93	15.89
Noordgrens	2011	375.52	694.40	94465.47	131.44	13.88	12.56	85.36	12.51	12.61	71.23	2.31	16.58	16.53
Noordgrens	2012	363.11	672.30	85441.67	126.30	13.42	13.61	84.93	12.30	12.19	70.93	2.33	15.47	15.56
Farm	Harvest Year	Days Growth	Area To Harvest	Total Tons	TPH	Sucrose %	Fibre %	Purity %	Rel RV %	RV %	Moisture %	Non-sucrose %	Ton/Rv/Ha/Ann	Ton/RRV/Ha/Ann
Umhlatuzi Valley Sugar	2009	369.53	1001.50	117825.73	118.85	14.41	13.18	85.70	13.17	13.19	70.04	2.53	15.72	15.75
Umhlatuzi Valley Sugar	2010	361.24	992.66	107612.02	110.33	14.00	13.67	86.70	12.83	12.88	70.30	2.29	14.33	14.31
Umhlatuzi Valley Sugar	2011	376.88	1061.30	126853.73	122.44	14.57	13.02	86.44	13.23	13.33	70.19	2.40	15.85	15.82
Umhlatuzi Valley Sugar	2012	361.52	961.70	113563.48	120.78	14.18	13.67	86.21	13.02	12.95	70.15	2.31	15.89	15.93