Evaluating Terra MODIS Satellite Sensor Data Products for Maize Yield Estimation in South Africa

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Abstract

The Free State Province of the Republic of South Africa contains some of the most important maize-producing areas in South Africa. For this reason this province has also been selected as a Joint Experiment for Crop Assessment and Monitoring (JECAM, 2012) site representative of South Africa.

The Terra (EOS AM-1) research satellite carries the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. Two data products which are used in this research, created by the National Aeronautics and Space Administration (NASA) from the MODIS sensor, are the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI).

Objective yield points (OYP) are Global Positioning Points (GPS) that fieldworkers visit to record certain yield related data, including a final objective yield. Three research studies utilizing Terra MODIS data were performed. Study one utilised objective yields from the 2001/2002, 2004/2005 and 2005/2006 growth seasons for three provinces in South Africa. In study two, the 2006/2007 growth season OYP were extracted for the Free State province only. NDVI was downloaded from United States Geological Survey (USGS) for study one and two and extracted into a GIS for comparison with the OYP. For the Free State pilot study, study three, OYP from the 2001 to 2010 growth seasons were used. MODIS NDVI and EVI data were obtained from the Wide Area Monitoring Information System WAMIS portal for the data set of 35 points.

Statistical analysis was done on the data of studies two and three. The 2006/2007 dataset yielded a R^2 of 0.47 for all 225 points and 0.51 for the medium growth cultivar data only (186 data points), while the 2001 to 2010 growth season yielded an R^2 of 0.63 for the medium yield group. Therefore it is concluded that Terra MODIS NDVI and EVI data can be utilized for maize yield estimation on points.

1. Introduction

The Free State province contains some of the most important maize production areas in South Africa and is the main grain producing province in South Africa (Blignaut *et al*., 2009). It is situated between 23º and 28º East and 25º and 31º South and production in the Free State is a good indicator of the country's national production.

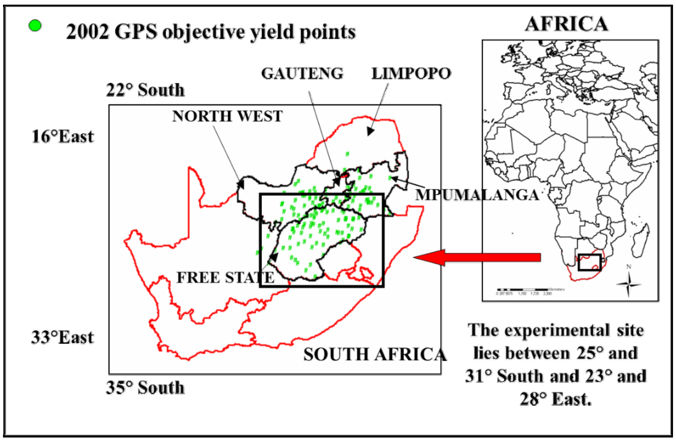

Figure 1. South Africa and Free State province study areas.

Generally South African maize production is divided into two primary areas, a dry western area (Western Free State and North-West provinces) and a wet eastern area (Eastern Free State, Gauteng, Mpumalanga and KwaZulu-Natal provinces) (Schultze *et al.,* 2001).

Usually the planting of summer maize in South Africa occurs from September to early February. Maize plants mature on average from 120 to 165 days after planting. There are 10 distinct growth stages for maize plants (Hanway, 1966). Stage 1 (30 days) is from planting day to emergence. By the end of stage 2 (dekad 4 to 5), 8 leaves have unfolded completely (a dekad is a ten day period). In stage 3 (dekad 6), the potential number of kernels and the ear size can be determined. In stage 4 (dekad 7), damage to the leaves can cause yield loss. Sufficient rainfall is critical during stages 1 to 4 (dekads 1 to 7). Stage 5 (dekad 8 to 9) marks the flowering stage where all the leaves are fully unfolded. Pollen starts shedding. The flowering stage in maize is the most critical period in the development of a maize plant's yield, and at this stage kernels begin to develop.

In stage 6 (dekad 10), leaf loss can result in the absence of any kernels at the tip of the ear. At stage 7 (dekad 11), the kernel mass is 50% of the final mass. NDVI, it is postulated can indicate the efficiency with which the kernels can be fed via photosynthesis. By stage 10 (dekad 14), the kernels are biologically matured, plant and husk leaves are changing colour and the plants are drying out. This is reflected in a decrease in NDVI. Historically NDVI is most successful to simply and quickly identify vegetated areas and their "condition". Once the feasibility to detect vegetation had been demonstrated, users tended to also use the NDVI to quantify the photosynthetic capacity of plant canopies (Sellers 1985).

The EVI, a standard product by NASA, became extremely popular with users due to its ability to eliminate background and atmosphere noises, as well as its non-saturation, a typical NDVI problem (Huete et al, 2002). This study sets out to confirm the relationship between NDVI, EVI and maize plant photosynthetic activity and maize yield under South Africa's variable climatic conditions. Initially the soil moisture requirement of the maize plant is low and builds up to a maximum during the flowering period. Thereafter the moisture requirement progressively decreases until the plants are physiologically mature. The moisture requirement is at its highest approximately two weeks before and two weeks after pollination, which occurs at stage 5 (dekad 8 to 9). During this period (dekads 6 to 11) the first critical stages of grain development will take place (PANNAR, 2012).

Maize is particularly sensitive to a shortage of water 30 to 40 days either side of flowering (around day 70 after planting). This stage of the plant's growth (between dekad 3 to dekad 13) is known as the "critical period" (Figure 2). The effects of water deficiency at different stages of growth on maize yield (FAO, 2012), (Figure 2) co-insides with the Window period (Frost, 2006).

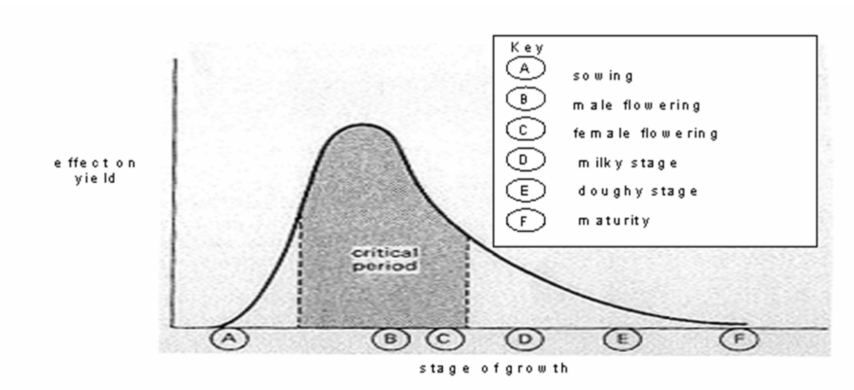

Figure 2. Effects of water deficiency at different stages of growth on maize yield (FAO, 2012).

The purpose of this study was to investigate the value of NDVI and EVI as estimators of maize yield in South-Africa.

2. Material and Methods

This paper addresses three different studies. Firstly the 2001/2002, 2004/2005 and 2005/2006 objective yield data were analysed using the "Window model", (Frost, 2006) and mathematically verified for the North West, Mpumalanga and Free State Provinces (Table 1). The Window model is a maize yield estimation timing model, developed using data from the 2001/2002 growth season. This model is useful in certain circumstances to establish when in the season the NDVI or EVI can be used for yield prediction. Secondly the 2006/2007 growth season data for the Free State province were analysed and thirdly a Free State pilot study was undertaken using OYP-data located at five specific pilot study areas from the 2001 to 2010 growth season's (Du Rand, 2012). Studies two and three were analysed using Multiple Regression analysis for the Free State province only. In study two NDVI was used whereas in study three NDVI and EVI data were utilised. Most of the objective yield points were located in the Köppen Zone 5(Schulze 1947) (cool, summer rainfall areas (BSwk)).

2.1 Objective Yield Data

The objective yields were surveyed and randomly selected from results of the stratified point frame system used by the National Crop Statistics Consortium (NCSC). Within the fields objective yield surveys were undertaken using a number of randomly generated OYP. These points were surveyed three times during, and once at the end of the growth season.

Field workers also gather information regarding white or yellow maize, planting date, irrigated or dry land and cultivar. The measurements of cobs and kernel counts obtained from these surveys are used in formulae (Frost, 2006) to derive plant population and a predicted objective yield figure for each of the GPS points in the maize field. Each growth season's OYP's were at different locations each year.

2.2 Terra MODIS Satellite Imagery

The Terra (EOS AM-1) research satellite carries the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor (NASA, 2013). Two of the data products created by the National Aeronautics and Space Administration (NASA) from the MODIS sensor are the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI).

The NDVI is created by normalizing the Red and Near-Infra-Red bands in the following manner (Sellers 1985):

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \qquad [1]$$

Where: NDVI = Normalised Difference Vegetation Index
NIR = Near Infrared wavelengths
VIS = Visable wavelengths

EVI is computed using this equation (Huete et al, 2002):

$$EVI = G \times \frac{(NIR - RED)}{(NIR + CI \times RED - C2 \times Blue + L)} \qquad [2]$$

Where: EVI = Enhanced Vegetation Index
NIR= Near Infrared wavelengths
C1 & C2 = Coefficients of the aerosol resistance (6, 7.5)
Blue = Blue wavelength,

L = Canopy background adjustment (1)
G = Gain Factor (2.5)

EVI corrects for some distortions in the reflected light caused by the particles in the air as well as the ground cover below the vegetation. The EVI data product also does not become saturated as easily as the NDVI when viewing areas of the Earth with dense vegetation (NASA, 2012). Two different sources of Terra MODIS data were used. For studies one and two, NDVI was downloaded from United States Geological Survey (USGS) (USGS, 2011) and extracted into a GIS for the 2001/2, 2004/5, 2005/6 and 2006/2007 growth seasons OYP's. For the third study in the Free State, making use of OYP data from the 2001 to 2010 growth season, Terra MODIS NDVI and EVI data were obtained from the Wide Area Monitoring Information System (CSIR, 2012).

2.3 Rainfall data

Rainfall coverages that were used in the first study (2001/2002, 2004/2005 and 2005/2006 growth season) for the three mentioned provinces were produced from rainfall data extracted from the Agricultural Research Council, Institute for Soil Climate and Water (ARC-ISCW) and South African Weather Service (SAWS) climate databases. Annual rainfall surfaces were interpolated using the long-term rainfall surface (Malherbe, 2006) as a trend for interpolation between stations. The Inverse Distance Weighted (IDW) interpolation technique was used. The temporal resolution of the rainfall surfaces is dekadal (10-day period), while the spatial resolution is 1 km (Malherbe, 2006).

2.4 Data extraction and analysis

For studies one and two, NDVI extraction was done in an ArcGIS environment. 16-day composite NDVI and dekadal rainfall values were extracted per OYP for dry land white maize throughout the growth season. Extracted data were transferred to spreadsheets. The 16-day NDVI data and 10-day rainfall data were synchronised by converting the extracted 16-day MODIS NDVI data to dekadal NDVI, through averaging. The dataset was divided into test- and analysis data. Next the NDVI and rainfall values were synchronized with age of maize plant by using the recorded OYP planting date information. For all three studies, OYP were structured into 3 yield categories: Low yield (L) (<2.5 ton/ha), medium yield (M) (2.5 to 4.5 ton/ha) and high yield (H) (> 4.5 ton/ha).

Average NDVI and average rainfall values were calculated and plotted per yield class. For study one, a statistical level of confidence was established using a standard deviation calculation for the 2001/2, 2004/5 and 2005/6 growth seasons for the three mentioned provinces (see Table 1).

The input data for the Free State pilot study, study three, consisted of the 45 GPS points at five test sites across the Free State. The locations were: Bothaville, Reitz, Bloemfontein and two sites at Jakobsdal. Objective yields spanned different growth seasons (2001 to 2010). The Terra MODIS

8-day NDVI & EVI data were obtained from Wide Area Monitoring Information System (WAMIS) portal for the specified GPS points (CSIR, 2012).

2.5 The Window Method Approach

The Window Method, study one, is based on plotting average NDVI,-EVI or -rainfall against age of the maize plant. Yield Prediction Windows were identified which are the age categories where spectral separation appeared to start and end and where NDVI and EVI showed promise for use in yield prediction. The statistical accuracy assessment (Table 1; Frost C, 2006) that was done in study one, on growth seasons 2001/2, 2004/5 and 2005/6, for the three mentioned provinces, is defined as the total percentage of times that the NDVI or rainfall value of the test data were within one standard deviation of the average of the corresponding yield class of the analysis data for every dekad.

2.6 Statistical Analysis

Forward Regression Analysis (Thiebaut and Steffens, 2011) with NDVI (Studies two and three) and EVI (Study three) values were used to predict yield. Study two (2006/7) and study three (2001 to 2010) Free State data was analysed using SAS 9.2 software (SAS Institute Inc., 1999). The NDVI data were grouped into 11 groups for the 16-day NDVI -and 22 groups for the 8-day NDVI data. The NDVI groups were labelled*: G01- G11 & G01- G22* for each 16-day- and 8-day recording; from plant to harvest respectively. The 22 EVI groups were named *G01- G22.* The variables, *Maximum NDVI or EVI* values were calculated by fitting a parabola on the NDVI/ EVI versus group data *(G01- G11* or *G01- G22)*. *Optimum NDVI* or *EVI period* was obtained from the parabola-fit. The variable *Area1* is the area under the parabola obtained from the NDVI/ EVI values. The variable *Area2* was estimated with the area (trapezium method) obtained from the NDVI or EVI values (Section 3.2).

3. Results

3.1 The Window Model

For study one, average NDVI and average rainfall, for study two, average NDVI and for study three average NDVI and EVI distribution graphs per yield class were plotted against the age of maize. From Figures 3 to 6 average NDVI Prediction Windows were between days 40 and 170 after planting. The average NDI and EVI prediction windows for the 2001 to 2010 growth seasons were from day 80 to 120 after planting (Figure 7 and 8). The average EVI per yield class showed greater spectral separation than the average NDVI.

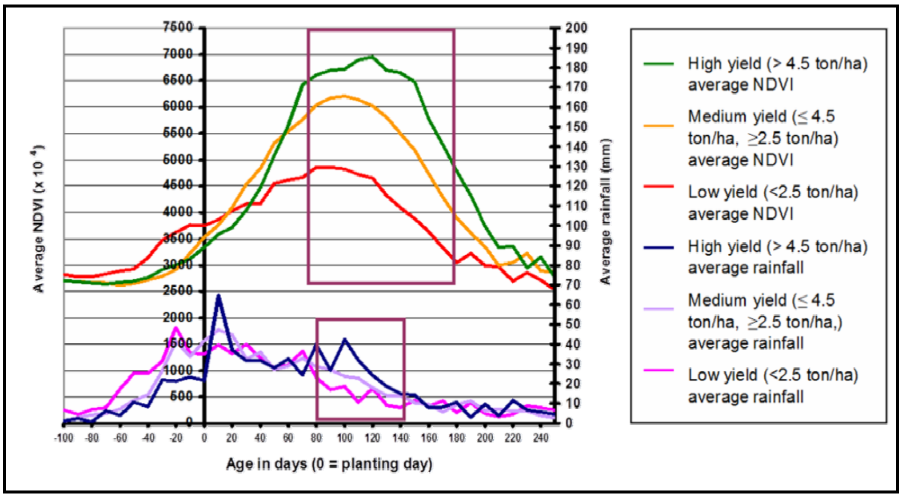

Figure 3. 2001/2002 average NDVI & average rainfall curves.

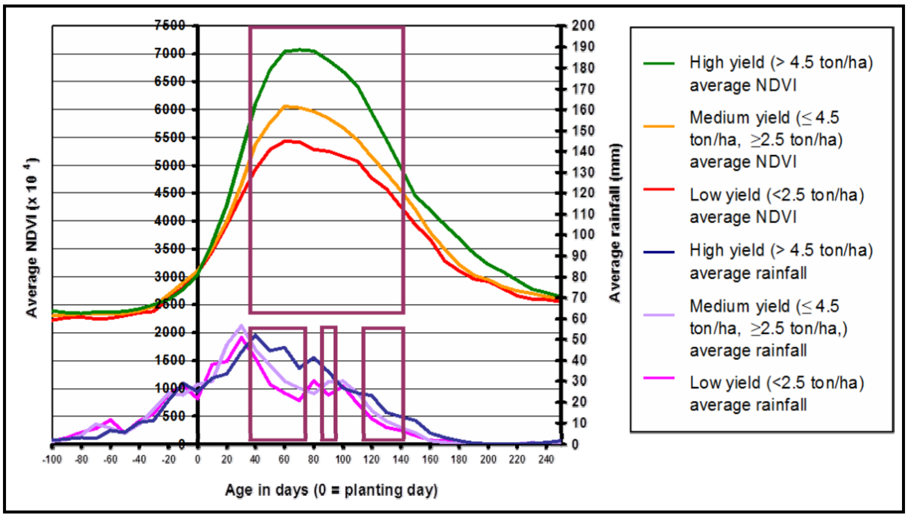

Figure 4. 2004/2005 average NDVI & average rainfall curves

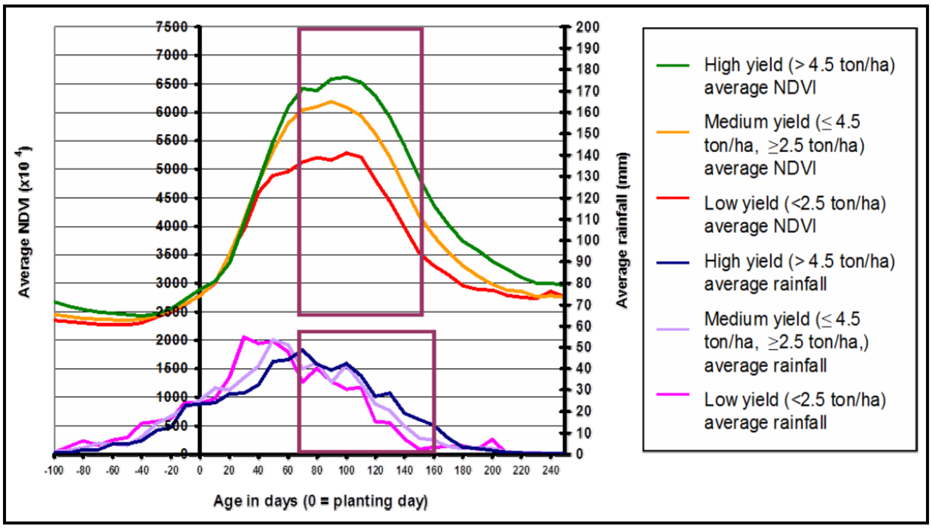

Figure 5. 2005/2006 average NDVI & average rainfall curves.

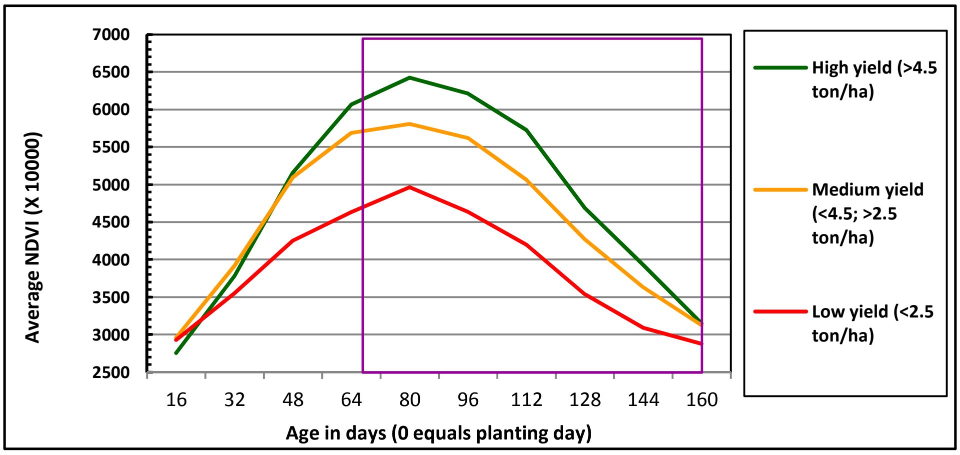

Figure 6. 2006/2007 average NDVI curves.

The prediction window in Figure 6 is wide and the spectral separation between the curves is similar than in Figures 3 to 5. Study three's NDVI curves and Window Period (Figure 7) appeared narrower than in Figures 3 to 6. The average EVI curves in Figure 8 show greater separation between the classes but the same Window Period as compared against Figure 7.

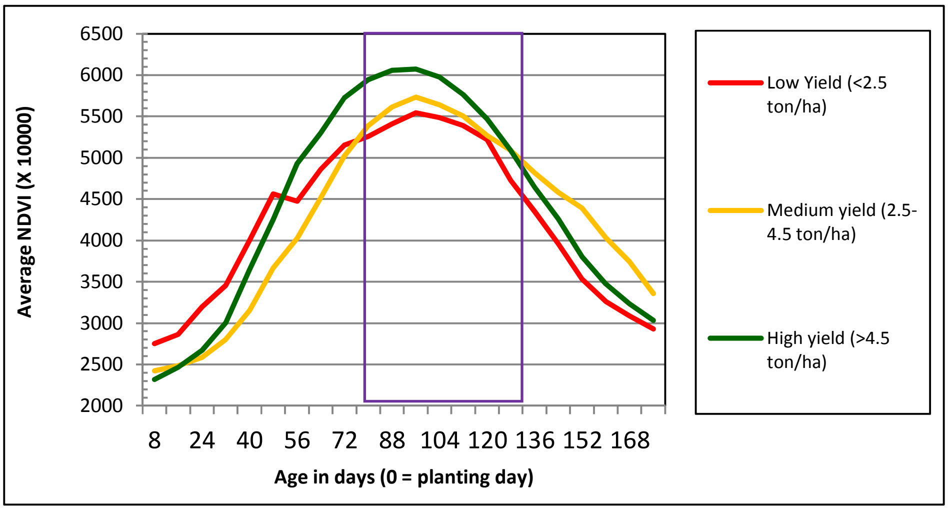

Figure 7. 2001 to 2010 average NDVI curves (45 points).

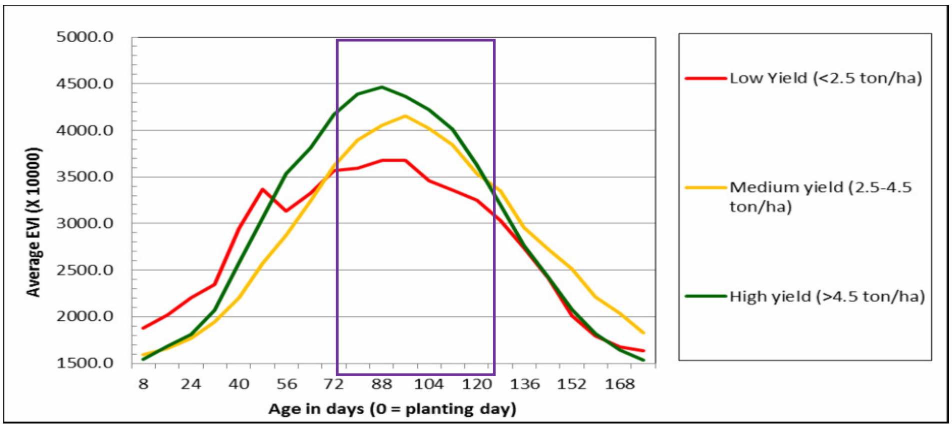

Figure 8. 2001 to 2010 average EVI curves (45 points).

In order to establish the usefulness of the Window Model for yield prediction, the percentage of times that the NDVI or rainfall value of the test data were within one standard deviation of the average of the corresponding yield class of the analysis data for every dekad, were calculated and illustrated in Table1. Table 1 tests the usefulness of the Window Model of figures 2 to 5 (Study 1).

Table 1. Mathematical model verification results.
L = low, M=medium, H=high (section 2.6)

Growing season & Window period	Average NDVI: % of time within 1 STDEV during window period	Average NDVI: Optimum estimation day	Average rainfall: % of time within 1 STDEV during window period	Average rainfall: Optimum estimation day
2001/2002: (days 70 to 170 after planting)	76.6%: L: 84.5% M: 58.5% H: 86.6%	Day 70 after planting: 81.9% L: 87.8% M: 67.3% H: 90.6%	82.5%: L: 85.4% M: 68.0% H: 94.0%	Day 160 after planting: 93.8% L: 92.7% M: 88.8% H: 100.0%
2004/2005: (days 40 to 140 after planting)	73.5%: L: 79.5% M: 62.3% H: 78.6%	Day 130 after planting: 87.5% L: 87.5% M: 81.0% H: 94.1%	81.0%: L: 84.1% M: 77.1% H: 81.8%	Day 90 after planting: 85.9% L: 87.5% M: 76.2% H: 94.1%
2005/2006: (days 70 to 150 after planting)	77.9%: L: 93.7% M: 67.0% H: 73.1%	Day 130 after planting: 82.1% L: 100.0% M: 62.2% H: 84.2%	84.6%: L: 92.1% M: 70.6% H: 91.2%	Day 150 after planting: 93.7% L: 100.0% M: 81.1% H: 100.0%

For the Free State data, study two (2006/7 growth season) and study three (the 2001 to 2010 Free State pilot study), a statistical approach was followed to estimate the yield by the use of NDVI (study two and three) and EVI data (Study three).

3.2 Statistical models

Study Two: Free State 2006/2007 data set – 11 NDVI groups (G1-G11):

Statistical analysis of the three yield groups separately yielded lower R^{2}'s, than when all (N=225) points (all type of cultivars together) were analysed, which yielded an R^2 of 0.47

$$y = -5.07 + 0.00016(Area2) + 0.0033(G9) + 0.0007(G10) - 0.00075(G11) \quad [3]$$

For the medium cultivars analysed separately (N=186) for the Free State 2006/2007 data the model obtained an R^2 of 0.51.

$$Yield = -3.91215 + 0.00134\,(NDVIMMax) - 0.00075425\,(G07) + 0.00058315\,(G08) + 0.00126\,(G10) - 0.00098253(G11) \quad [4]$$

The *NDVIMax* alone obtained an R^2 of 0.4**;** r=0.63 ($p<0.001$). By looking at the *linear* graphs of yield versus each x variable in the regression model, this is the best and most accurate model of all, and a good R^2 for this type of data was obtained. [3] and [4] can be confidentially used for maize estimation for the Free-State and with climate conditions as in 2006/2007.

Study Three: Free State 2001 to 2010 data set – 22 NDVI groups (G1-G22):

The medium yield group (N=21) yielded an $R^2 = 0.63$;

$$y = -1.7 + 0.41(\textit{Optimum period}) + 2.55(G8) + 3.01(G13) - 7.8(G20) \quad [5]$$

which was higher than for the low and high yield groups respectively. Making use of all 42 points, an R^2 of 0.30 was obtained.

$$y = 3.14 – 18.8(G4) + 10.68(G5) + 7.31(G7) \quad [6]$$

Study Three: Free State 2001 to 2010 data set – 22 EVI groups (G1-G22):

The high yield groups

$$y = 2.95 + 33(G2) – 41.8(G4) + 21.55(G6)) \quad [7]$$

and medium yield groups

$$y = 2.8 + 3.23(G12) – 3.5(G20) \quad [8]$$

resulted in very similar R^2 values ($R^2 = 0.46$ and $R^2 = 0.45$) respectively.

When al 42 objective yield points were used, an R^2 of 0.36 was found

$$y = 5.6 – 34.4(G4) – 19.4(G7) + 15.9(G8) – 15.0(G9). \quad [9]$$

4. Conclusions related to the Window- and Statistical models

4.1 NDVI and EVI use for yield prediction.

While individual values of NDVI and EVI vs. objective yield had low R^2 and had a ‘cloud effect’ when plotted, grouping OY points into the three yield classes produced ‘average’ graphs which showed a better agreement in terms of low, medium and high maize yield for all the data sets.

For simplicity maize age was determined as if emergence took place between dekad 1 and 3 with rain being present after planting. The Window Model (Frost, 2006) was subjectively superimposed onto the graph showing where divergince takes place between the three average curves. The resulting Window Periods are an indication of when average NDVI or average EVI data can be confidently used to make yield predictions.

4.2 Statistical conclusions (NDVI and EVI use for yield prediction).

For study two (Free State, 2006/2007), 16-day MODIS NDVI data set with 11 NDVI groups (R^2=0.47 & 0.51) it is concluded that splitting the data into high, medium and low yield classes yielded lower R^2 than to evaluate all points together. The two models; that utilizes all the data points, as well as the medium growth cultivars, are the best and most accurate of all the regression models (different datasets) because the model had enough data values (N=225 and N=186) and good R^2's to estimate crop yield were obtained. The variable, *Area2* (Equation [3]) was included in the regression model i.e. the optimal area under the NDVI curve over time. *NDVIMax* (Equation [4]) was the maximum value of the NDVI values over the growth season.

For the third study (the Free State 2001 to 2010), the 8-day NDVI data set with 22 NDVI groups was used. There were too few data points to generate an accurate yield model, although more frequent NDVI measurements were available, which on the other hand counts to the model's advantage. The medium yield group gave a better result than analyzing the low and high yield group separately, and a better result than analyzing the yield groups together. From the NDVI groups (64, 104 and 160 days after planting (equation [5])) and the variable, *optimum period* of the parabola obtained from the different NDVI included into the forward regression model, the model's R^2 gave a value of 0.63.

For the third study (Free State, 2001 to 2010 data set) with 22 EVI groups, the medium yield group gave the best model although the high yield model could predict yield earlier (from as early as day 48 days after planting) (Equations [6] and [7]). The high yield class R^2 was 0.46 and medium yield groups obtained very similar R^2's (R^2 = 0.46 and R^2 =0.45) respectively.

The objective yield points used in study three were from different rainfall seasons, which resulted in different NDVI and EVI values. It is concluded that Terra MODIS NDVI and EVI data can be successfully utilized for maize yield estimation on point data in the Eastern Free-State.

This is further confirmed by a study done in Hungary by Bognár, (2004), where the "robust method's" target was to establish a direct mathematical relationship between the properties that a satellite can sense of a crop covered area and the yield of that crop which was within a 10% error margin. The relationship between NDVI, EVI and maize plant photosynthetic activity and maize yield is thus confirmed under South Africa's variable climatic conditions. The average Window Periods indicate that between day 40 and 170 after planting, the NDVI and EVI can confidently be used for early yield prediction.

4.3 Limitations

The Objective yield data set is rich with information and should be utilized for crop estimation exercises, but it has certain limitations which have to be kept in mind. NDVI values are not an absolute indication of the potential yield, but of plant vigor. Plant vigor is not always an indication of the amount of pollination, seed development or grain fill. The summer maize producing areas in South Africa are not homogeneous. In study three, NDVI and EVI were compared over different agro-climatological zones and different growth seasons (2001 to 2010 data set). Study one compared OYP over different GPS locations each year. Short, medium and long growers were analysed together, except in one part of study two (2006/7 growth season) where only medium growers were used for analysis, which gave good results.

5. Recommendations

It is recommended to use 2006/2007's model for medium growers in the Eastern-Free State with climate circumstances as in 2006/2007 ([4]) alternatively, planting date maps have to be created by using the Inverse Distance Weighted method of interpolation from planting dates obtained from Objective Yield data. A long-term average planting date map should be created from the planting date maps from objective yield data. A long term average objective yield map should also be created from objective yield data over all the available growth seasons. The overlay product would be a map which depicts average planting date and average yield for an area or pixel.

It is suggested to use a long term Terra MODIS NDVI and EVI image and compare a current NDVI or EVI image in the Window period and produce an anomaly map. This resulting map would depict average age and yield of the maize as well as a positive, same or negative NDVI difference/anomaly.

Further the long term average objective yield map can be classified to depict whether the pixel falls within a low, medium or high yield area (according to the class breaks used in this study). Further research is required to link average low, medium and high yields with average low, medium and high NDVI or EVI classes.

To create a long term NDVI/EVI model, the same GPS locations in the same fields for at least 10 years with at least 100 or more GPS points used preferably with 8-day in-stead of 16-day data should be used. Factors such as temperature, clay percentage, soil depth, rainfall and heat units might be investigated to refine the model.

Planting date maps for each growth season were different and it is thus important to compare maize of the same age when using NDVI or EVI imagery for an area. Preferably in future compare NDVI/EVI maps for maize of the same age using Start of Season or Onset of Rains map (CSIR, 2012).

Following work by Bognár (2004) who found that higher resolution data worked for field level (10 meters) but low resolution data yielded good results for region and country level, a similar approach can be used. Average NDVI and average EVI values show promise in terms of yield prediction, but more research might establish its worth for e.g. for large areas like districts or provinces. Use OY data to interpolate yield for larger areas like provinces or districts and use NDVI / EVI for these regional estimates / per district/province.

The Schulze (2007) mean potential yield map or the long term average yield map created from objective yield data might be used to delineate homogenous areas for which to predict yield from NDVI or EVI imagery. Area and point predictions made from these yield maps should be tested against objective yields, yields obtained from farmers, e.g. yield data from The Department of Agriculture, Forestry and Fisheries (DAFF) and data from the South African Grain Information Service (SAGIS).

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