ACTUAL CROP WATER USE IN PROJECT COUNTRIES: A SYNTHESIS AT THE REGIONAL LEVEL

Robina Wahaj[1], Florent Maraux[2] and Giovanni Munoz[1]

---

[1] Land and Water Development Division of FAO (Food and Agriculture Organization of the United Nations).
[2] Visiting Scientist from CIRAD (Centre de coopération internationale en recherche agronomique pour le développement) to FAO.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

The reports in this special series are the result of a multi-country research activities conducted under the GEF funded project: *Climate Change Impacts on and Adaptation of Agro-ecological Systems in Africa*. The main goal of the project was to develop multipliable analytical methods and procedures to assess quantitatively how climate affects current agricultural systems in Africa, predict how these systems may be affected in the future by climate change under various global warming scenarios, and suggest what role adaptation could play. The project has been implemented in 11 countries: Burkina Faso, Cameroon, Ghana, Niger and Senegal in west Africa; Egypt in north Africa; Ethiopia and Kenya in east Africa and South Africa, Zambia, and Zimbabwe in southern Africa. The study countries covered all key agro-climatic zones and farming systems in Africa. This is the first analysis of climate impacts and adaptation in the Africa continent of such scale and the first in the world to combine cross-country, spatially referenced survey and climatic data for conducting this type of analysis.

The analyses reported in this series focus mainly on quantitative assessment of the economic impacts of climate change on agriculture and the farming communities in Africa, based on both the cross-sectional (Ricardian) method and crop response simulation modeling. The cross sectional analysis also allowed for assessing the possible role of adaptation. Moreover, the project employed river-basin hydrology modeling to generate additional climate attributes for the impact assessment and climate scenario analyses such as surface runoff and streamflow for all districts in the study countries.

The Centre for Environmental Economics and policy in Africa (CEEPA) of the University of Pretoria coordinated all project activities in close collaboration with many agencies in the involved countries, the Agriculture and Rural Development (ARD) Department of the World Bank, the World Bank Institute (WBI), the Food and Agriculture Organization (FAO), Yale University, the University of Colorado, and the International Water Management Institute (IWMI). The project received supplemental funding from TFESSD, Finnish TF, NOAA-OPG, and CEEPA. We are grateful for the invaluable contributions of all these institutions and all individuals involved in this project. All opinions presented in this report series and any errors in it are those of the authors and do not represent the opinion of any of the above listed agencies.

Rashid Hassan, Project Leader
CEEPA, University of Pretoria

Ariel Dinar, Project Manager
ARD, World Bank

EXECUTIVE SUMMARY

This report aims to synthesize the results of a crop water use study conducted by country teams of the GEF/World Bank project *Regional Climate, Water and Agriculture: Impacts on and Adaptation of Agro-ecological Systems in Africa*. It also presents the results of the second phase of the study based on climate change scenarios, conducted by the South Africa country team.

The actual evapotranspiration of five commonly grown crops – maize, millet, sorghum, groundnuts and beans – in two selected districts were analyzed by six country teams. In addition, two country teams also analyzed other crops grown in the districts. The regional analysis shows that the actual yield of the different crops – specifically of maize and groundnuts – improves with an increase in actual evapotranspiration, although the gap remains wide between actual and potential yield and actual and maximum evapotranspiration, especially for the rainfed crops. This highlights the importance of improved water management if agriculture is to play an important role as a source of food security and better livelihoods.

In general, the study results give realistic evapotranspiration and actual yield values for maize, sorghum, millet, beans and groundnuts. The average values for crop water productivity for these crops are within the common published ranges, with maize and sorghum being the most water efficient crops in terms of water use. It is important, however, to highlight the vulnerability of maize to water stress and the increased risks to the viability of rainfed farming systems based on this crop.

The first phase of the study provided a framework for the analysis of future crop water use as affected by climate change in Africa. The second phase of the analysis, that includes climate change impact on crop water use, was conducted by the South Africa country team. This analysis was performed for maize, using the methodology developed by the FAO (Food and Agriculture Organization) that is used together with CROPWAT to assess future crop water requirement and use. The results of the second phase of analysis show that a 2°C increase in the temperature and a doubling of CO_2 concentration in the atmosphere will shorten the growing period of maize, which will result in decreased crop water requirement and use.

It is recommended that this analysis is extended to the other crops as well as to the other countries to be able to get a clearer picture of the changing pattern in crop water use of the major crops grown in the project countries.

1. Introduction

The GEF/World Bank project *Regional Climate, Water and Agriculture: Impacts on and Adaptation of Agro-ecological Systems in Africa* seeks to investigate the effects of climate change on different agro-ecosystems in Africa. This study is one of the first analyses of climate change impacts on agriculture and how it adapts in Africa. Although there have been some studies of climate impacts in the continent, it is still unclear how Africa will be affected by climate change and how its agriculture will adapt.

This study aims to provide holistic empirical evidence incorporating three main approaches – crop response simulation modeling, hydrological modeling and economic analysis – to fully understand the role that climate plays in Africa today and how that might change with global warming.

There is enough scientific evidence to show that any significant change in climate on a global scale will affect local agriculture and therefore the world's food supply. In several geographical areas there has been a considerable number of studies on how and up to which level future climate changes will affect agricultural production. These kinds of studies are subject to all the complexities that characterize natural agro-ecosystems, so no single approach is valid in all circumstances. One of the most common approaches in climate change impact studies is to use agro-environmental simulation models. Several of these have been developed to study specific aspects of this impact, and some studies have explored possible future scenarios combining the use of different existing models.

For the agricultural sector the complexity comes from the confrontation between normal climate variability and climate changes and the dynamics of farming systems. Worldwide farming systems represent the responses to constraints and opportunities from the surrounding environmental and socio-economic conditions. A change in these constraints and opportunities generates changes in the farming systems. Therefore, in agricultural production, analyzing the impacts of climate change must be done considering possible changes or adaptation to farming systems.

The project, in its launch workshop in December 2003, adopted the Ricardian approach[3] to assess the economic impact of climate change on African agriculture. To further increase the understanding of this impact it was recommended to initiate parallel analysis in crop simulation and river basin hydrological modeling. Crop modeling offers a powerful tool for studying in a very short period of time the possible consequences of changing conditions. Thus, modeling is commonly used to analyze the possible effects climate change will have on agriculture. These impacts are manifold and the interaction among different parameters is complex to analyze and not always fully understood; modeling may often be considered an oversimplification. However, it is one of the best existing tools as it allows users to test many scenarios in a short period of time and if the limitations of the approach are properly recognized the results may provide adequate insights into the climate change impacts on agriculture.

The FAO (Food and Agriculture Organization) was requested to help the national teams develop a unified approach in crop simulation modeling. Provision of training was envisaged

---

[3] The Ricardian approach uses statistical analysis of data across geographic areas to separate climate from other factors (such as soil quality) that explain production differences across regions, and uses the estimated statistical relationships to assess impacts of climate change. The approach assumes farmers optimize their farming systems.

as an FAO input. A first training workshop on *Crop response simulation and river basin hydrology modeling* was held in June 2003 in Ghana.

The country teams used the CROPWAT program to assess potential and actual crop water use of the selected crops in the selected districts. The project countries foreseen to participate in the study and in the regional analysis are presented in Table 1. The study was conducted in two phases. In the first phase a minimum of five crops – beans, groundnuts, maize, millet and sorghum – were selected for two districts in each country for the analysis on present crop water use. In the second phase, the countries would use climate change scenarios to forecast the future water requirement of these crops. For this second phase a particular methodology was developed to take into account changes in both temperature and CO_2 concentrations for the calculation of crop water use under the climate change scenarios with the use of CROPWAT. This methodology is presented in Appendix 1. It has already been used by the South Africa country team and the results were presented in the project workshop held in Spain in December 2004. These results are presented in Appendix 2 of this report.

This report presents the final results of the regional synthesis of the first phase of the study that analyzes the water use of the selected crops in the project countries, and the results of the second phase of the study based on climate change scenarios conducted by the South Africa country team.

2. Methodology

The project countries have diverse farming systems covering a wide range of agro-climatic zones. The national teams selected at least two districts (see Figure 1) each representing two different agro-ecozones of their respective countries with varying climatic conditions, cropping and farming systems. Figure 2 shows the broad farming systems in Africa[4] as defined by the FAO and World Bank (2001), and Table 2 summarizes the information about the main features of the selected districts in the project countries. The following are the main characteristics of the farming systems in the project countries:

- *Agro-pastoral millet/sorghum:* Rainfed sorghum and pearl millet are the main sources of food of this farming system and are rarely marketed, whereas sesame and pulses are sometimes sold. Land preparation is by oxen or camel, while hoe cultivation is common along river banks. Livestock are kept for subsistence and transportation. The main factor for vulnerability is drought, leading to crop failure, weak animals and distress sale of assets.

- *Irrigated:* This system is characterized by large and small irrigation schemes with high population density and small farm size. Crop failure is generally not a problem but livelihoods are vulnerable to water shortages.

- *Cereal root cropped mixed:* Here cereals such as maize, millet and sorghum are widespread. Intercropping is common. This farming system is found predominantly in

---

[4] A farming system is defined as a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate (FAO and World Bank, 2001). Although the country teams did not use this classification of farming systems, they used their national classification of both agro-ecozones and farming systems.

the dry sub-humid zone. Livestock is abundant. The main factor for vulnerability is drought. The agriculture growth potential is high.

- *Forest based:* In this system farmers clear new fields from the forest every year, thus practice shifting cultivation. These fields are cultivated for two to five years – first cereal or groundnuts and then cassava – and then abandoned to bush fallow for seven to 20 years. However, because of increased population density the fallow periods are progressively being reduced. Physical isolation and lack of roads and markets pose serious problems.

- *Highland perennial:* This farming system is based on perennial crops such as bananas and coffee and is complemented by cassava, sweet potatoes, beans and cereals. Land use is intense and holdings are very small: more than 50% of the landholdings are smaller than half a hectare.

- *Highland temperate mixed:* In this system small grains such as wheat and barley are the main staple, complemented by peas, lentils, broad beans and Irish potatoes. Cattle are used for plowing. The major factor for vulnerability is climate: early and late frosts at high altitude cause a decrease in yield and crop failures are not uncommon in cold and wet years.

- *Large commercial and smallholder:* This farming system lies mainly in the semi-arid and dry sub-humid zones of South Africa and Namibia. It comprises two distinctive types of farms: scattered smallholder farms and large commercial farms. Both types are largely mixed cereals-livestock systems. Small farmers often survive by means of off-farm income from employment. Poor soils and drought are the sources of vulnerability.

- *Maize mixed:* This farming system lies mainly in East and southern Africa with altitudes from 800 to 1500 meters. It also contains scattered small-scale irrigation schemes. The climate varies from dry sub-humid to moist sub-humid. The population density is high and farm sizes are small. The main staple is maize and the main sources of cash are food crops such as maize and pulses, tobacco and coffee; livestock such as cattle and small ruminants; and migrant remittances. Socio-economic differentiation is considerable, due mainly to irrigation.

- *Pastoral:* This system is based mainly on sheep, goats and camels and is located largely in the arid and semi-arid zones. These zones are sparsely populated, with more densely populated areas around irrigation settlements. Socio-economic differences are considerable. The main source of vulnerability is great climatic variability and consequently a high incidence of drought.

Among the project areas selected to be studied within the countries, Egypt presents the driest environment (with rainfall less than 100mm per year), whereas the wettest locations are in the Bobo Dioulasso district of Burkina Faso (with an average rainfall of about 1000mm per year). In Egypt, unlike the other countries participating in the study, agricultural production is totally dependent on irrigation. There are also large differences in the climatic conditions and agro-ecozones within some countries, such as Ethiopia, Senegal and Zambia.

The majority of the project countries have farming systems with subsistence farmers practicing manual farming using family labor for crop production. In Egypt, South Africa, and the Chipata district in Zambia,[5] large farmers practice commercial, mechanized and intensive farming. Maize, millet, groundnuts, sorghum and beans are the main crops grown in the project countries, especially where rainfed agriculture is practiced. In Egypt the main crops are cotton, wheat, maize and citrus fruits. Commercial farmers in South Africa grow fruit such as apples and pears. For this study, the country teams chose the following five crops for the analysis: maize, millet, sorghum, groundnuts and beans.

The actual water use of these crops was assessed using the FAO methodology outlined in FAO Irrigation and Drainage (I&D) Papers Nos. 33 and 56 (FAO 1979, 1998) and the CROPWAT program. CROPWAT is a decision support system developed by the Land and Water Development Division of FAO. Its main functions are to calculate reference evapotranspiration, crop water requirements and crop irrigation requirements in order to develop irrigation schedules under various management conditions and scheme water supply and to evaluate rainfed production, drought effects and efficiency of irrigation practices.[6]

CROPWAT can be used in combination with the CLIMWAT database,[7] which includes monthly average data from a total of 3262 meteorological stations from 144 countries, including all the project countries of this study.

Thirty years' average climate data from 1961–1991 was used for assessing potential crop evapotranspiration by all the project countries except Burkina Faso and Ethiopia. Some country teams collected the climate data directly from their respective meteorological stations, others used the CLIMWAT database.[8] The country teams also collected production data for a number of years. Table 3 shows the years and sources of data used for the analysis.

3. Actual crop water use

The methodology used in this study to assess actual crop water use is outlined in FAO I&D 56 (1998) which draws heavily on the procedures for predicting yields when all the climate, soil and crop parameters are known, as described in FAO I&D 33 (1979) *Yield response to water*. In fact, this approach is the inverse procedure of the more widely known and used one developed in the same publication, which aims to predict crop yield based on the actual crop water use (ETa) and maximum crop water requirement (ETc).

This approach proposes to estimate actual evapotranspiration (or actual crop water use), after having estimated the stress factor from the ratio of actual to potential yield. The complete procedure is explained in the following paragraphs.

Crop evapotranspiration or crop water use can be assessed by multiplying the reference evapotranspiration (ETo) by the crop coefficient (Kc) (see Equation 1). The reference evapotranspiration is calculated by using climatic data, with the Penman-Monteith equation:

---

[5] In other provinces/districts of Zambia, agriculture production is mainly rainfed, thus yield varies with varying rainfall.

[6] http://www.fao.org/ag/AGL/aglw/cropwat.stm

[7] CLIMWAT is published as Irrigation and Drainage paper No. 49 (FAO 1994) and includes a manual which describes the use of the database with CROPWAT.

[8] During the training workshop in Ghana in 2003, and later in Egypt in 2004, it was decided that 30 years' average climate data would be used for the analysis. It was also decided that this data would be extracted from FAO's CLIMWAT database.

$$ETc = Kc \times ETo \tag{1}$$

where ETc = Crop evapotranspiration

ETo = Reference evapotranspiration

Kc = Crop coefficient.

The ETc calculated through Equation (1) is the evapotranspiration from crops grown under optimal management and environmental conditions, with good water availability and no limitations of any other input. The crop evapotranspiration, also know as actual crop water use, in this report is calculated by using a water stress coefficient Ks and/or by adjusting Kc for all kinds of other stresses and environmental constraints. In this report the actual crop water use is calculated by using the following formulae:

$$ETc_{actual} = Ks \times ETc \tag{2}$$

Where ETc_{actual} = Actual crop evapotranspiration

Ks = Water stress coefficient.

FAO Irrigation and Drainage Paper No 33 (FAO 1979) proposes to assess the yield response factor using the following equation:

$$\left[1 - \frac{Ya}{Ym}\right] = Ky\left[1 - \frac{ETa}{ETm}\right] \tag{3}$$

Combining Equations 2 and 3 and solving for the stress factor:

$$Ks = 1 - \frac{1}{Ky}\left[1 - \frac{Ya}{Ym}\right] \tag{4}$$

where

Ya = actual yield

Ym = maximum/potential yield[9]

Ky = yield response factor. Ky describes the reduction in relative yield according to the reduction in ETm caused by soil water shortage

ETa = ETc actual = actual crop evapotranspiration

ETm = maximum/potential evapotranspiration. ETm = ETc

Ks = Water stress coefficient.

4. Crop water use in the project countries

The FAO methodology was used by the project countries to assess the actual crop water use of the selected crops in the different districts.[10] As expected, the results show that the potential crop water requirement (ETm) is highest in arid and semi-arid areas, and among crops maize has, in general, the highest potential crop water requirement. It is important to note here that the crop water use of the irrigated millet and sorghum is higher than the crop water use of rainfed maize, which is also logical as there is more water available to evapotranspire to the irrigated crops. See Table 4 for results reported by the country teams.

However, the crop water use of some of the crops seems unrealistic. For example, actual evapotranspiration of sorghum in the Miesso district in Ethiopia and of all the crops in the Aguie district in Niger seems to be underestimated for their actual yield. These discrepancies probably stem from the fact that the average yield data are not used for the same years as those of climate data. Moreover, water is only one of the several factors affecting actual yield and low figures for yield do not always explain the reasons behind these values. The FAO methodology uses actual and potential yields for assessing crop water use, and any inconsistency in these two yields will result in misleading values of actual crop water use. For consistency, such results were not included in the regional analysis.

4.1 Actual yield versus actual crop evapotranspiration

Crop water use, in general, is directly related to the yield of the crop, if all the other factors remain constant. Although the analysis in this report is based on the actual data collected from different sources where many factors affected the crop yield, the linear correlation between the actual water used by maize and actual yield is very strong (see Figure 3).[11] The actual yield of maize increases 13 times with a four times increase in the water use. The trend shown in Figure 3a matches a similar trend presented in a recent study by Zwart and Bastiaanssen

---

[9] Maximum yield of a crop (Ym) as defined in FAO (1979) is 'the harvested yield of a high-producing variety, well-adapted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases do not limit yield. Information on yields indicates the maximum yield that is obtained under actual farming conditions, with a high level of crop and water management'.

[10] In case of Egypt, it was also possible to analyze crop water use of other additional crops because of the information provided in the report. The South Africa team has analyzed other additional crops as well.

[11] This curve should, in fact be, polynomial. However, since neither crop water use, nor actual yield is at its maximum in the selected districts, only the initial slope of the polynomial curve is apparent in the results.

(2004) in which the published data from ten countries with a big sample size (n = 233) was used for analyses.

In the case of rainfed maize, actual yield increases from 0.8 tons/ha when the actual crop water use is 212mm to 2.26 tons/ha when the actual crop water use is 381mm.[12] These values are realistic according to the published values for water use efficiency. Among the selected crops, maize is the least drought resistant and needs water particularly at the flowering stage. The figure also shows that there would not be any more maize yield below 150mm of evapotranspiration. As expected, farmers prefer to grow drought resistant crops (sorghum, pearl millet, groundnuts, etc.) in the dry Sahelian areas (see Table 2). Growing maize in wet areas, or with timely irrigation, can therefore improve the harvest tremendously. This trend is also apparent for groundnuts (see Figure 3b), although the number of samples is too small to draw any conclusion.

4.2 Actual evapotranspiration of maize crop

Maize is by far the most common crop grown in all the selected districts. It has replaced some other, better adapted, crops such as sorghum and millet, which over time may ensure better food security. It is grown in climates ranging from temperate to tropical and tolerates high temperatures. The ideal temperature for maize ranges from 15°C (frost free) to 45°C.

The actual evapotranspiration of maize for selected districts of the project countries is shown in Figure 4. The results from the country teams show that, in general, the actual water use by maize is rather low, which does not allow it to produce a good yield. Maize (medium maturity) requires between 500 and 800 mm of water (depending on the climate) to give the maximum yield (FAO 1979). In the selected districts, crop water use by maize is highest for irrigated crops (in Egypt) followed by the crops cultivated in the sub-humid agro-climatic zones of Burkina Faso, Ethiopia and Senegal – in these countries maize is grown mainly by farmers in the southern parts, which are more humid. Evapotranspiration by rainfed maize is least in semi-arid and dry zones because of erratic rainfall, leading to low yields. The crop water productivity[13] of maize is also high compared with other crops grown in the same districts. The average crop water productivity of maize in the districts studied in this project is 0.8 kg/m^{3,} which is in line with the range 0.8 to 1.6 kg/m^3 published by the FAO (1979).

4.3 Actual evapotranspiration of other crops

Millet, groundnuts, sorghum and beans are the other crops selected by the project country teams for the analysis. Figure 5 shows the actual evapotranspiration of these crops in the selected districts. Millet is the only crop that is not irrigated in any of these districts. It is drought resistant and therefore can survive long dry spells, which might explain the reason for there being no particular pattern of crop water use related to agro-climatic zones. Moreover, a complementary explication is that a farmer, in general, has several soil and crop management options for dealing with dry conditions. He can manage the crop density, or the sowing date, or the fertilization strategy. All these options, except the sowing date, are not taken into account by CROPWAT, and evidently cannot be presented here as explanatory factors.

The actual evapotranspiration of sorghum increases from semi-arid to sub-humid agro-climatic zones (see Figure 5), and in districts with no irrigation it also increases with the

---

[12] The actual crop water use was assessed following the procedures described in the methodology section of this report.

[13] Crop water productivity is the amount of water required per unit of yield. This productivity will vary greatly according to the crop species.

increase in total yearly rainfall. Sorghum is one of the most drought resistant crops and is extensively grown under rainfed conditions as a food crop and also as fodder. An attempt is made (see Figure 6) to show the relationship between average rainfall over a year and crop water use. Considering the problem of the inconsistency of the real time field data, this relationship seems to be very good and shows the vulnerability of a crop dependent on variable rainfall. Crop water use by sorghum is highest in the Giza district of Egypt as the crop is irrigated there. If we compare the crop water requirement with actual crop water use for rainfed sorghum (see Table 4), it is in line with the rainfall pattern as well.

Sorghum and millet are two important food crops after maize in the project countries. Because they are well suited to the dry conditions of semi-arid zones, they are part of farmers' strategy for guaranteeing food production and ensuring that the risk of failure in dry spells will be low.

Groundnuts are also frequently grown under rainfed conditions, however, this crop is less drought resistant than sorghum. The results from the selected districts show that the yield in the Giza district (Egypt) is relatively good (3 tons/ha) for the amount of water the crop consumes (455mm) as compared to its water requirements under optimal conditions (720mm) The reason for this is that irrigation makes it possible to provide water to the crop at the critical growth stages. Although the gap between the crop water requirement and the water actually used in the Diourbel district of Senegal is close to that of the Giza district, the yield is not as good (0.7 tons/ha in Diourbel) because the crop is rainfed and the flexibility to supply water at the critical growth stage does not exist.

Beans grow well in areas with medium rainfall, but the crop is not suited to the humid, wet tropics. Moreover, its ideal minimum and maximum temperatures for growth are 10°C and 27°C (FAO 1979). The results for the selected districts, presented in Figure 5 and Table 4, show that the actual crop water use is rather low compared with the crop water requirement calculated with CROPWAT (see Table 4), even when the crop is irrigated. The water requirement for maximum production of a 60 to 120 day crop varies between 300mm and 500mm (FAO 1979). The maximum crop water use in the selected districts is less than 200mm, which is consistent with the fact that short cycle varieties have been used.

Average crop water productivity values for sorghum, beans and millet are in line with the ranges published in FAO (1979) and elsewhere. These values are slightly lower for groundnuts (see Table 5). Although the actual reasons for these low figures are not known they are not necessarily due to water use.

5. Water efficient crops: Example from Egypt and South Africa

This section of the report will briefly touch on water use of various crops within the selected districts. Because of the availability of relevant information for the analysis, the districts selected for this section are from Egypt and South Africa. South Africa also reported water withdrawal for different crops, making it easier to conduct this analysis.

5.1 Water use by crops in Egypt

The selected districts/governorates in Egypt are mainly irrigated, thus making it possible to grow two crops a year and also perennial crops. Crop diversity is high: the country team reported about 25 crops grown in the two districts, including summer crops, winter crops, industrial crops and food crops. An attempt is made here to show the percentage of area cultivated under different crops and the percentage of water use (see Figure 7). The figure shows that cotton and tomatoes use a relatively high percentage of water compared with the area cultivated. The intensive use of water resources for these crops is justified as they are cash crops and can give a high return. Unfortunately, data on water diversion to different crops was not available; therefore it is not possible to compare water diversion to water use, but as these crops are mainly irrigated it can be assumed that actual water use is almost completely dependent on irrigation.

5.2 Water use by crops in South Africa

A wide range of crops – both irrigated and rainfed – are grown in the two selected districts in South Africa. The high altitude of the Caledon district makes it possible to grow deciduous fruit, such as apples, pears, peaches and wine grapes. In the dryland hilly areas of this district wheat and barley are the main crops grown. Maize is the main crop grown in the Kroonstad district, followed by winter wheat. Figure 8 presents the crop water use of the irrigated crops, water withdrawal for these crops, and their potential and actual yield in the two districts in South Africa. Apples and pumpkins in the Caledon district and sorghum and groundnuts in the Kroonstad district seem to have smallest gap between potential and actual yield, while maize followed by wheat in the Kroonstad district and lucerne followed by dry beans in Caledon have the largest gap between potential and actual yield. These differences between the potential and actual yield may be due to the way the potential yield was assessed, as it is a debatable criterion and depends on the weight given to non-water factors (such as average fertilization, average diseases management, etc.). According to the criteria used by the evaluator, the potential yield vary considerably in a region under study.

It is interesting to note that sorghum in Kroonstad and pumpkins and apples in Caledon have only a reduced gap between their actual water use and water requirement (ETa/ETc). However, the gap between the actual water use and the water requirement of maize in Kroonstad is the second smallest after sorghum (0.29 for maize and 0.31 for sorghum); it is not reflected in the ratio of actual to potential yield of maize in this district.

Water withdrawal[14] as compared to crop water requirement is highest for dry beans and potatoes in the Caledon district and wheat and sunflower in the Kroonstad district. This ratio is lowest for wine grapes in Caledon and groundnuts and maize in Kroonstad. There seems to be a relatively strong relationship between the ratio of water use to crop water requirement and the ratio of actual to potential yield of different crops in the Caledon district (see Figure 9).

6. Conclusion and recommendations

This report aims at synthesizing the results of the crop water use study conducted by the country teams of the GEF/World Bank project *Regional Climate, Water and Agriculture: Impacts on and Adaptation of Agro-ecological Systems in Africa.* Present crop water use of five commonly grown crops, including maize, millet, sorghum, groundnuts and beans in two selected districts, were analyzed by six country teams. In addition, two country teams also analyzed other crops grown in some districts.

The analysis shows that the actual yield of the different crops – specifically of maize and groundnuts – improves with an increase in actual evapotranspiration, although the gap

---

[14] Note that no irrigation efficiencies have been accounted for in this analysis.

remains wide between the actual and potential yield and actual and maximum evapotranspiration, especially for rainfed crops. In case of irrigated crops, the yields are better even when the crop water use is relatively low as compared to their respective water requirement as a result of flexibility in water supply at the critical growth stages of the crops. Rainfed maize and sorghum seem to be performing better in terms of crop water use in the sub-humid climate as compared to semi-arid Sahelian climatic conditions due to better rainfall. This corroborates the well-known fact that water is among the main limiting factors in several African farming systems and therefore irrigation could play an ancillary role in agricultural development.

In general, study results give realistic values for maize, sorghum, millet, beans and groundnuts. evapotranspiration and actual yield. The average values for Crop Water Productivity (CWP) for these crops are within the common published ranges. Maize and sorghum appear to be the most water efficient crops grown in the districts. Maize, however, is the crop that is the most sensitive to water stress among the crops studied and should therefore be grown only where good availability of water can be guaranteed. It should therefore be grown under irrigation or only in rainfed areas where rainfall is reliable and the crop needs can be properly satisfied. This unfortunately is not the case in most of the districts studied.

If information about the current low reliability of rainfall patterns is combined with recent studies on possible changes in surface water availability, the interest in increasing the area under irrigation increases. In fact, de Wit and Stankiewicz (2006) predict that by the end of this century 25% of Africa will have reduced surface flows owing to diminishing rainfall.

It could be concluded, on the basis of results obtained, that this study provides a realistic and representative sample of African conditions, regarding:

- the diversity of agroclimatic and environmental conditions and the dominant cropping systems, and
- crops and their present water requirements, actual water use and expected yields.

The results of the first phase of study may be used as an initial picture, to which climate change scenarios can be applied. The estimated present crop water use of the main crops in the project countries provides the basis for the framework for simulating climate change scenarios and their impact on crop water requirement. For this purpose, the FAO has developed a draft methodology (see Appendix 1) that would allow CROPWAT to be used to analyze the effect of climate change on crop water requirement.

The analysis proposed in the draft methodology follows three steps:

1. Assessing change in the duration of different growth stages as affected by increased or decreased level of temperature and CO_2 concentration in the atmosphere.
2. Calculating crop water requirement by using the projected climate data and the new growth stages from step 1 in CROPWAT.
3. Recalculating the actual crop water use as described in the methodology section of this report.

This draft methodology has been used by the South African country team to calculate the impact of climate change on the crop water requirement of maize for three districts –

Lichtenburg, Kroonstad and Middelburg. The results of this analysis are presented in Appendix 2.

In South Africa, crop water use by maize as a result of elevated CO_2 concentration in the atmosphere and an increase in temperature of 2°C will shorten the total growing period by at least 16 days, and consequently crop water requirement will be decreased by 10%. It is estimated that actual crop water use will be reduced by 4% on average. It is recommended here that other country teams also conduct this analysis with climate change data. Moreover, it will be useful to carry out a similar analysis for other major crops.

REFERENCES

De Wit M & Stankiewicz J, 2006. Changes in surface water supply across Africa with predicted climate change. *Science 31* 311(5769): 5769 http://www.sciencemag.org/cgi/content/abstract/311/5769/1917

Diop M, 2006. Simulating impacts of climate variations on crop water use productivity in Senegal. CEEPA Discussion Paper No. 34, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Diouf O, 2000. *Réponses agrophysiologiques du mil (Pennisetum Glaucum (L.) R. BR.) à la sécheresse: Influence de la nutrition azotée*. Thèse présentèe en vue de l' obtention du grade de docteur en Sciences. (PhD thesis.) Faculté des Sciences. Laboratiore de Physiologie et d'Agrotechnologies Végétales. Université Libre de Bruxelles.

Durand W, 2006. Assessing the impact of climate change on crop water use in South Africa using CROPWAT. CEEPA Discussion Paper No. 28, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Eid H, El-Marsafawy S & Ouda S, 2006. Using CROPWAT to analyse climate change impacts on crop water use in Egypt. CEEPA Discussion Paper No. 29, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

FAO (Food and Agriculture Organization), 1979. Yield response to water. Authors, Doorenbos J & Kassam AH. Irrigation and Drainage Paper 33. Rome, Italy.

FAO (Food and Agriculture Organization), 1994. CLIMWAT for CROPWAT. Author, Smith M. Irrigation and Drainage Paper 49. Rome, Italy.

FAO (Food and Agriculture Organization), 1998. Crop evapotranspiration : Guidelines for computing crop water requirements. Authors, Allen RG, Pereira LS, Raes D & Smith M. Irrigation and Drainage Paper 56. Rome, Italy.

FAO & World Bank, 2001. Farming Systems and poverty: Improving farmers' livelihoods in a changing world. Authors, Dixon J & Gibbon D. Rome, Italy, and Washington DC.

Giogris K & Tarekegen D, 2006. Climate change impacts on crop yield and crop water use in Ethiopia. CEEPA Discussion Paper No. 31, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Moussa K M & Amadou M, 2006. Use of CROPWAT model to predict SMD and crops yield with climate change. CEEPA Discussion Paper No. 32, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Some L, Dembele Y, Ouedraogo M, Some M B, Kambire L F & Sangare S, 2006. Analysis of crop water use and soil water balance in Burkina Faso using CROPWAT. CEEPA Discussion Paper No. 36, Centre for Environmental Economics and Policy in Africa, University of Pretoria.

Tamala KT, 2004. CROPWAT exercise report for Zambia, unpublished project report.

Zwart SJ & Bastiaanssen WBM, 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton, and maize. *Agricultural Water Management* 69: 115–133.

Table 1: Project countries and selected districts for CROPWAT study

Country	Area (km^2)	No of districts	Nos. of districts selected by country teams*
Burkina Faso	273,719	301	4
Cameroon	466,307	10	3
Egypt	982,910	27	2
Ethiopia	1,132,328	65	2
Ghana	239,981	110	-
Kenya	584,429	48	6
Niger	1,186,021	36	2
Senegal	196,911	320	2
South Africa	1,221,943	372	4
Zambia	754,773	72	2
Zimbabwe	390,804	60	-

* Where no number is shown the CROPWAT study has not yet been conducted.

Table 2: Basic information on the farming system of the project countries

Country	Districts/ Province	Agro-climatic zone	Length of growing period (days)	Rainfall mm	Rainfed/ Irrigated	Major crops	Dominant cropping system	Farming systems (FAO and World Bank, 2001)
Burkina Faso	Bobo Dioulasso	Sub-humid	150	1000	Rainfed	Sorghum, millet, maize, rice, cotton	Small farmers / manual / Extensive	Cereal root cropped mixed
	Fada N'Gourma	Dry (Sahelian)	120	800	Rainfed	Millet, sorghum, maize, groundnuts, cow peas	Small farmers / manual / Extensive	Cereal root cropped mixed
Cameroon	Ambam	Humid		1500 – 4000	Rainfed	Cocoyams, cassava, banana	Small farmers / manual / Extensive	Forest based
	Bamenda	High savanna		2500	Rainfed	Oil palm, tea, potatoes, vegetables	Small farmers / manual / Extensive	Highland temperate mixed
	Garoua	Sahel savanna		950	Rainfed/ Irrig. cotton	Maize, millet, sorghum, cotton	Small farmers / manual / Intensive	Cereal root cropped mixed
Egypt	Khafr el-Sheikh	Desert	-	60	Irrigated	Cotton, wheat, maize	Small farmers / mechanized / Intensive	Irrigated
	Giza	Desert	-	20	Irrigated	Maize, wheat, tomatoes, citrus	Small farmers / mechanized / Intensive	Irrigated, pastoral
Ethiopia	Adama	Sub-humid		850	Rainfed	Maize, sorghum, haricot beans	Small farmers / manual / Intensive	Pastoral
	Miesso	Semi-arid		500	Rainfed	Sorghum, maize, haricot beans	Small farmers / manual / Extensive	Maize mixed
Kenya	Kiambu	Sub-humid		1100	Rainfed	Maize, beans, bananas, Irish potatoes, tea, coffee	Small farmers / manual/ Intensive	Maize mixed
	Laikipia	Semi-arid		600	Rainfed/ Irrigated	Maize, potatoes, tomatoes, beans, peas, onion, wheat, barley	Small farmers / manual / Extensive	Maize mixed
	Makueni	Semi-arid		1000	Rainfed/ Irrig. horticultural crops	Maize, beans, pigeon peas, cow peas, coffee, cotton	Small farmers / manual / Extensive	Maize mixed, pastoral

Table 2: (continued)

Country	Districts/ Province	Agro-climatic zone (Thornthwaite)	Length of growing period (days)	Rainfall mm	Rainfed/ Irrigated	Major crops	Dominant cropping system	Farming systems (Dixan et al, 2001)
Kenya	Migori	Sub-humid		700 – 1800	Rainfed	Tea, coffee, tobacco, beans, cassava, sorghum, maize	Small farmers / manual / Extensive	High land perennial
	Vihiga	Humid		1900	Rainfed	Maize, millet, sorghum, sugarcane, tea, coffee	Small farmers / manual / Extensive	Maize mixed
	Kwale	Semi-arid		450 – 1400	Rainfed/ Irrig. horticultural crops	Maize, sorghum, rice, beans, cow peas, tomatoes, capsicum, melons, kale	Small farmers / manual / Extensive	Maize mixed
Niger	Aguié	Semi-arid (Sahelian)	80	500	Rainfed	Millet, sorghum, cowpea, groundnuts	Small farmers / manual / Extensive	Agro-pastoral millet/sorghum
	Gaya	Dry (Sahelian)	110	700	Rainfed	Sorghum, millet cowpea, groundnuts	Small farmers / manual / Extensive	Agro-pastoral millet/sorghum
Senegal	Diourbel	Semi-arid (Sahelian)	100	500	Rainfed	Millet, groundnuts	Small farmers / manual / Extensive	Agro-pastoral millet/sorghum
	Kolda	Sub-humid	150	950	Rainfed	Millet, groundnuts	Small farmers / manual / Extensive	Cereal root cropped mixed
South Africa	Caledon	Mediterranean		700	Irrig. (6.2%) & rainfed	Wheat, barley, apples, pears	Large farms / mechanized / Intensive	Large commercial and smallholder
	Kroonstad	Mediterranean		550	Irrig. (0.69%) & rainfed	Maize, wheat, potatoes	Large farmers / mechanized / Intensive	Large commercial and smallholder
Zambia	Chongwe	Dry		700	Rainfed	Maize, sunflower	Small farmers / manual/ Extensive	Maize mixed
	Chipata	Sub-humid		900	Rainfed	Maize, groundnuts	Large farmers / mechanized/ Intensive	Maize mixed

Table 3: Years and source of the data used in the analysis

Country	Data*		Source climate data*
	Climate (including rainfall)	Production	
Burkina Faso	1962-2003		
Cameroon			
Egypt	1961-1990	1990-2000	Weather station
Ethiopia	1991-2001	1992-2002	Weather station
Kenya			
Niger	1961-1990	2003	National metrological service
Senegal	1961-1990		
South Africa	1961-1990	1993	CLIMWAT/SAPWAT
Zambia	1961-1990		CLIMWAT

* Where no information is given about the year and source, it was not found in the country reports or supplied otherwise.

Table 4: Actual crop water use of the selected crops in the project countries

	Country	District	Crop	ETo (mm)	ETm (mm)	Ky	Ya (t/ha)	Ym (t/ha)	Ks	Cropped area (ha)	ETa (mm)	Crop water use (mcm)
1	Burkina Fasso	Bobo-Dioulasso	Maize	596	480	1.25	1.4	4.0	0.48	61,430	230	142
			Sorghum	557	400	0.9	0.9	1.3	0.66	84,440	263	222
			Pearl millet	573	410	1.2	0.7	0.9	0.81	32,860	334	110
		Fada N'Gourma	Maize	633	512	1.25	0.8	3.0	0.41	13,750	212	29
			Sorghum	508	365	0.9	0.8	1.2	0.63	40,000	230	92
			Pearl millet	522	365	1.2	0.7	0.8	0.90	52,860	327	173
2	Cameroon	Ambam	Maize	413	267	1.25	0.6	2	0.44		159	
		Bamenda	Maize	570	382	1.25	0.5	2	0.44		153	
		Garoua	Maize	890	596	1.25	0.7	2	0.48		286	
3	Egypt	Khafr el-Sheikh	Maize	678	557	1.25	9	9	0.99	32,132	549	176
			Beans - dry	189	157	1.15	3	4	0.73	8,600	114	10
		Giza	Maize	825	676	1.25	6.6	9.3	0.77	45,463	521	237
			Beans - dry	310	258	1.15	2.6	3.6	0.77	98	198	0
			Groundnuts	835	720	0.7	3	4	0.63	1,590	455	7
			Sorghum	825	676	0.9	5.5	7	0.74	726	503	4
4	Ethiopia	Adama	Maize	563	532	1.25	2.3	3.5	0.72		381	
			Sorghum	469	469	0.9	2.7	4.5	0.55		257	
		Miesso	Maize	426	375	1.25	1.4	3.5	0.53		197	
			Sorghum	353	353	0.9	1.5	4.5	0.26		91	
5	Kenya	Kiambu	Maize	492	330	1.25	2.3	9.0	0.40	21200	133	28
			Beans - dry	419	264	1.15	1.0	2.5	0.48	17130	127	22
		Makueni	Maize	565	379	1.25	1.0	9.0	0.29	35700	109	39
			Beans - dry	463	292	1.15	0.4	2.5	0.27	16700	79	13
		Vihiga	Maize	495	332	1.25	2.4	9.0	0.41	14900	137	20
			Groundnuts	491	354	0.7	4.8	4.0	1.27	38	448	0.17
			Beans - dry	414	261	1.15	0.9	2.5	0.46	8600	120	10

Table 4: (continued)

	Country	District	Crop	ETo (mm)	ETm (mm)	Ky	Ya (t/ha)	Ym (t/ha)	Ks	Cropped Area (ha)	ETa (mm)	Crop water use (MCM)
	Kenya	Kwale	Maize	663	444	1.25	1.1	9.0	0.30	14238	134	19
			Beans - dry	509	321	1.15	0.5	2.5	0.29	5048	94	5
		Migori	Maize	588	394	1.25	3.8	9.0	0.54	18350	211	39
			Beans - dry	494	357	1.15	1.4	2.5	0.61	9550	218	21
			Sorghum	527	327	0.9	1.9	5.0	0.30	3653	98	4
		Laikipia	Maize	476	319	1.25	2.3	9.0	0.40	20900	129	27
			Millet	460	244	1	1.4	3.0	0.48	20	117	0.02
			Beans - dry	397	250	1.15	1.0	2.5	0.47	12400	117	15
6	Niger	Gaya	Millet	668	482	1.2	0.6	0.9	0.73	104,244	350	364
			Beans - dry	551	451	1.15	0.1	0.6	0.31	71,039	140	99
		Aguie	Millet	528	359	1.2	0.4	0.8	0.58	152,304	210	320
			Beans - dry	619	512	1.15	0.1	0.4	0.37	141,421	187	265
7	Senegal	Diourbel	Millet	383	450	1	0.5	0.8	0.63	135,887	283	385
			Groundnuts	394	403	0.7	0.7	1.2	0.45	78,968	181	143
		Kolda	Millet	556	439	1	0.9	1.2	0.73	80,957	320	259
			Groundnuts	549	380	0.7	1.1	1.3	0.75	83,151	283	235
			Maize	637	389	1.25	0.9	1.2	0.80	31,490	312	98
8	South Africa	Caledon	Beans - dry	510	371	1.15	0.2	3	0.19	629	70	0.44
		Kroonstad	Maize	759	575	1.25	0.79	7	0.29	88,805	167	148
			Sorghum	874	712	0.9	2.27	6	0.31	1185	220	3
		Lichtenburg	Maize	624	484	1.25	0.70	7	0.28	239,750	136	325
		Middelburg	Maize	740	581	1.25	2.40	7	0.47	130,718	276	360

Sources: Moussa and Amadou (2006), Giogris and Tarekegen (2006), Eid et al. (2006), Diop (2006)

ETo = Reference evapotranspiration
ETm = Maximum crop evapotranspiration
Ky = Yield response factor
Ya = Actual yield
Ym = Maximum achievable yield
Ks = Water stress coefficient
ETa = Actual crop evapotranspiration or actual crop water use
mcm = million cubic meters

Table 5: Average Crop Water Productivity (CWP) of the selected crops in the project districts

Crop	Average CWP (kg/m^3)	CWP range published in FAO (1979) and elsewhere* (kg/m^3)
Beans	0.44	0.30 – 0.60
Groundnuts	0.50	0.60 – 0.80
Millet	0.21	0.16 – 0.66
Sorghum	0.70	0.60 – 1.00

* The range for millet is taken from a PhD dissertation (Diouf 2000). The values are calculated on the basis of two years' experiments with different treatments, in Senegal. Ranges for rest of the crops are published in FAO (1979).

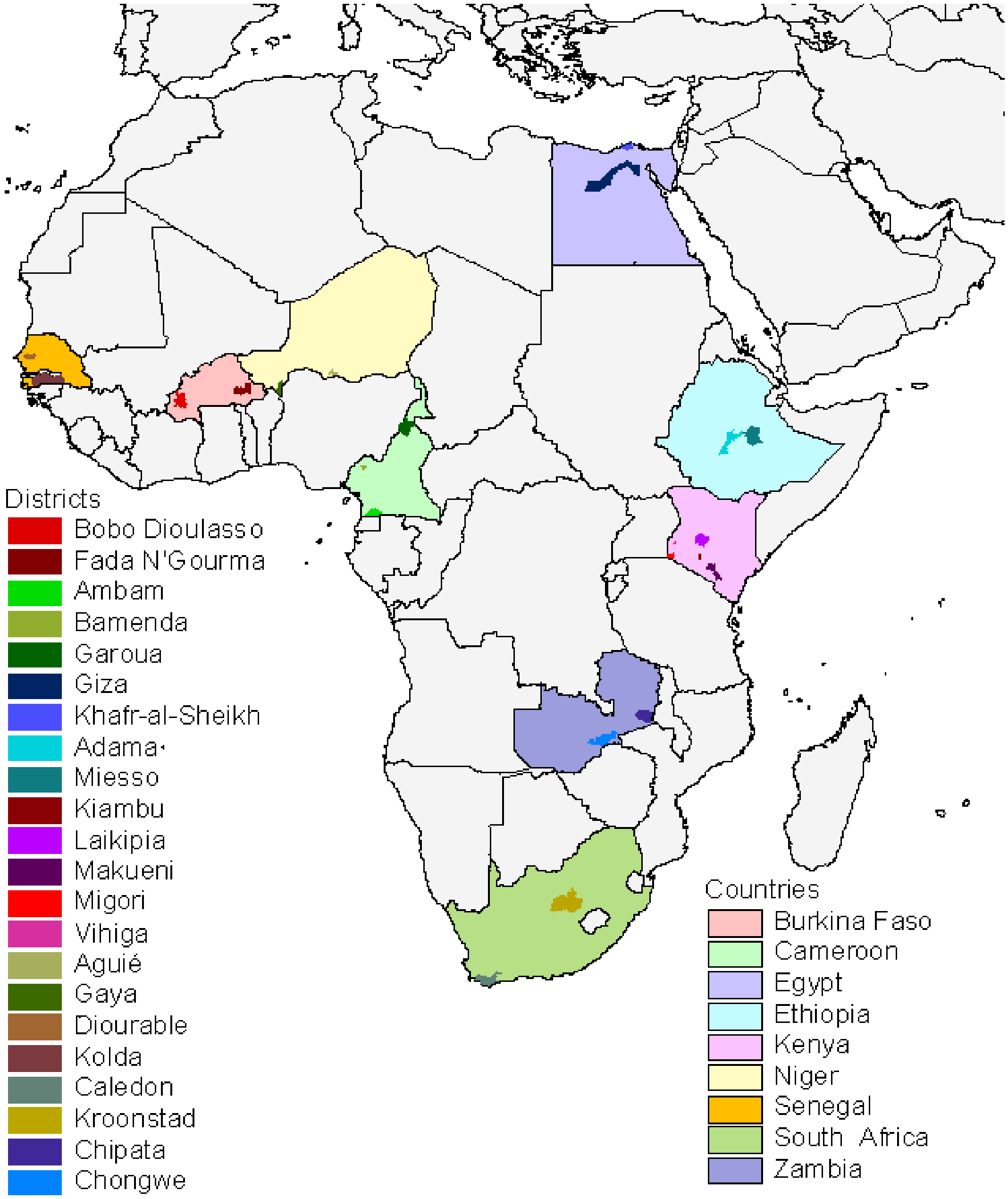


Figure 1: Selected districts for CROPWAT analysis in the project countries

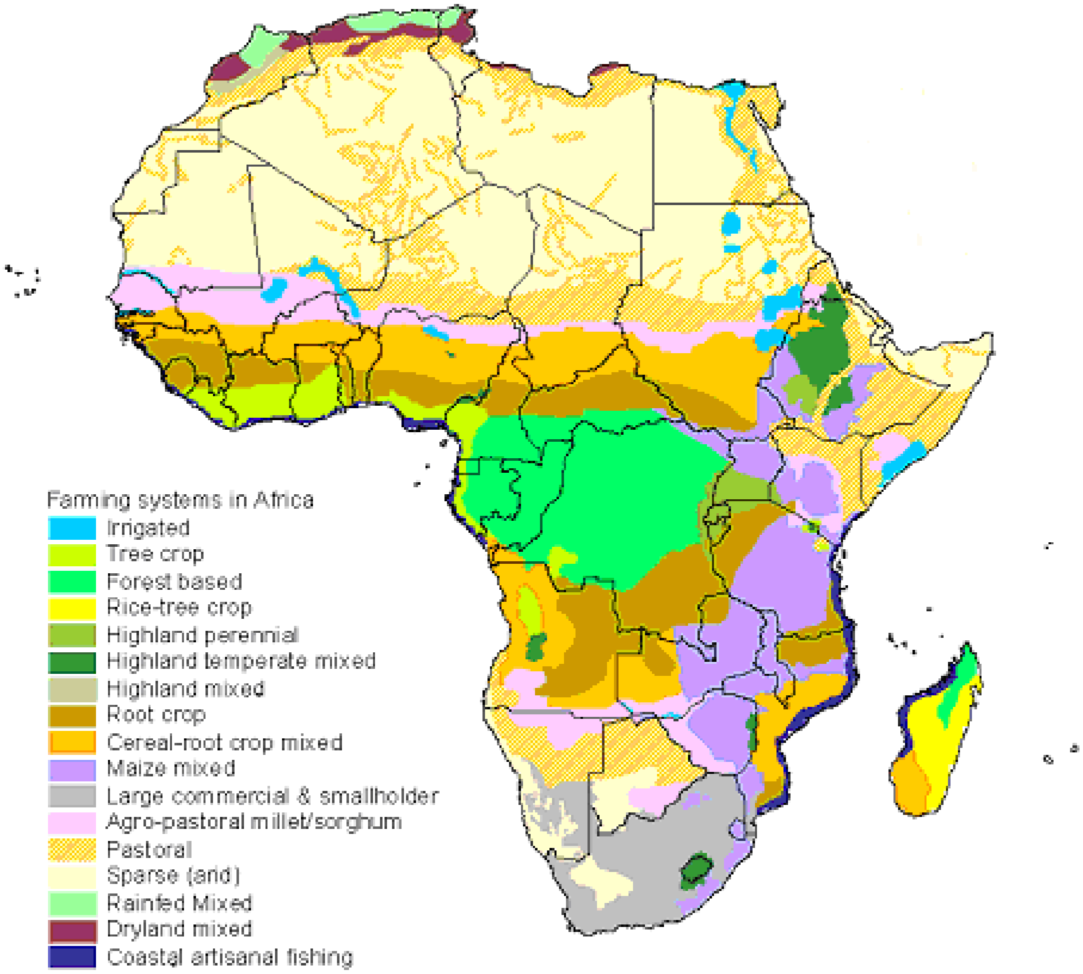
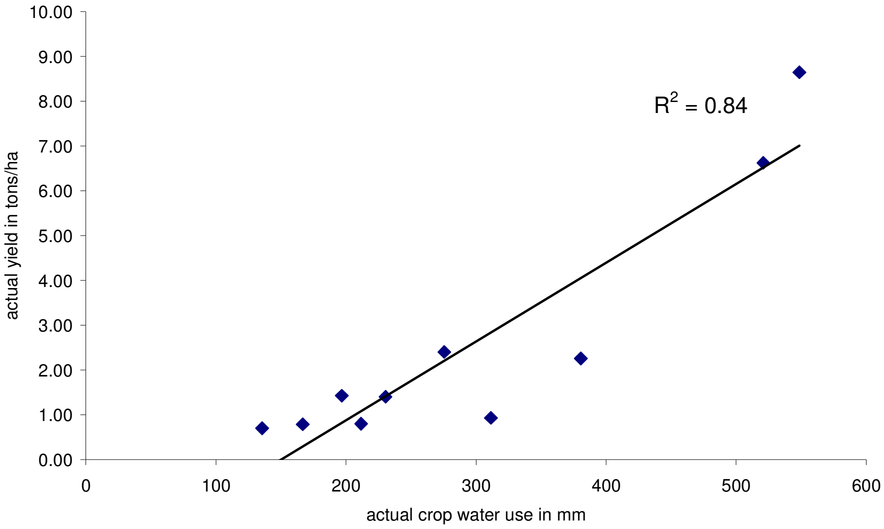
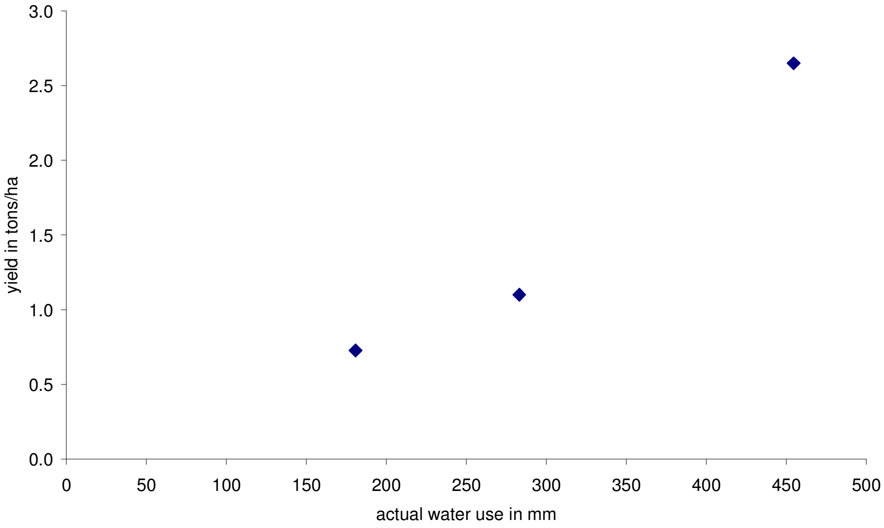


Figure 2: Farming systems in Africa (Adapted from FAO and World Bank, 2001)



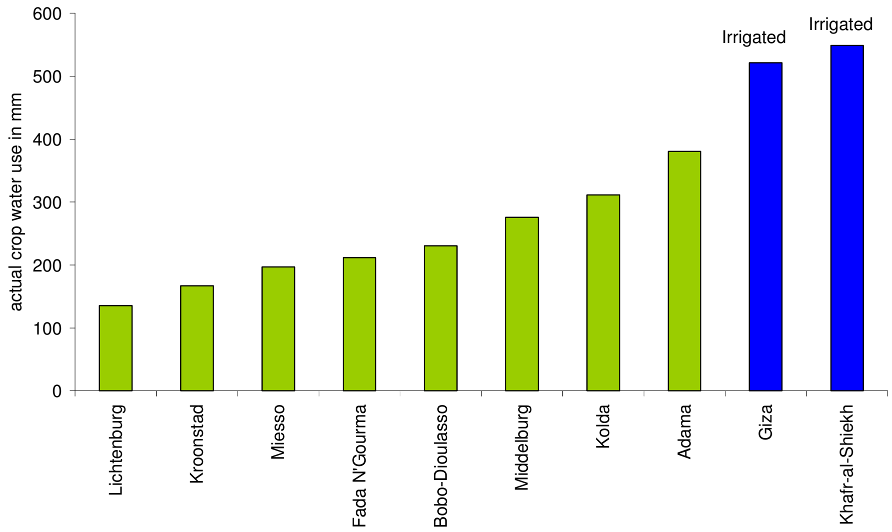
(a) Maize

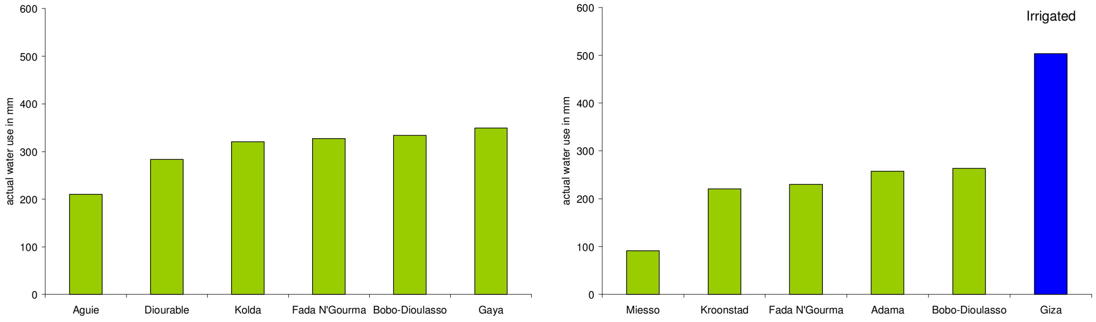


(b) Groundnuts

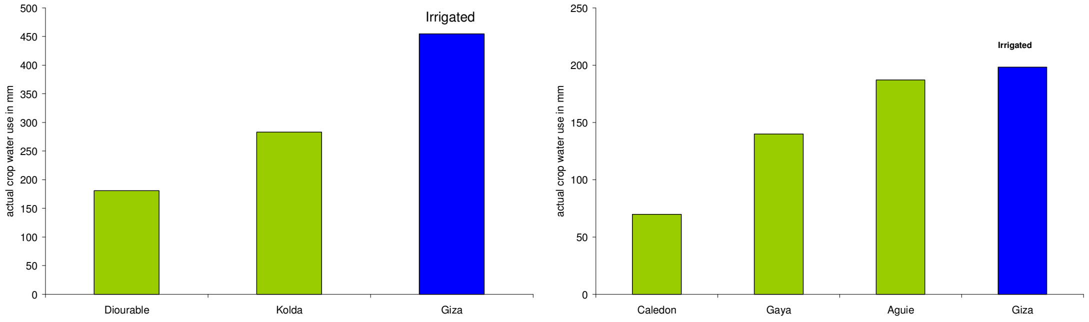
Figure 3: Actual crop water use versus actual yield of maize (a) and groundnut (b) crops in the selected districts in Africa

Figure 4: Actual crop water use by maize in the selected districts in Africa





millet sorghum



groundnuts beans

Figure 5: Actual crop water use by millet, sorghum, groundnut and beans in the selected districts in Africa

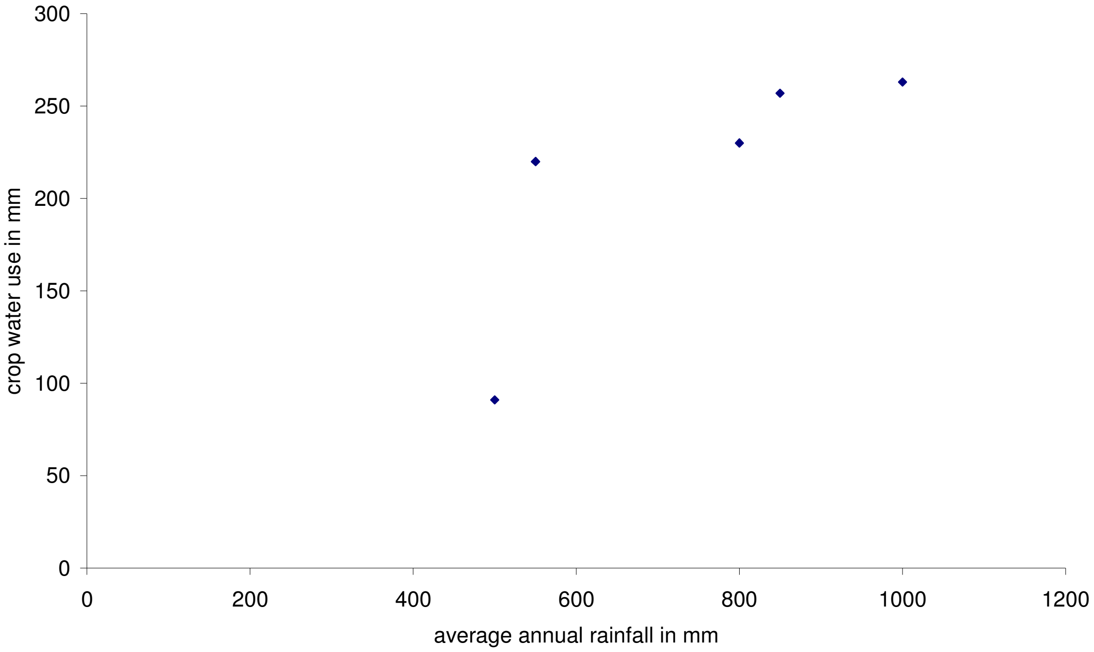
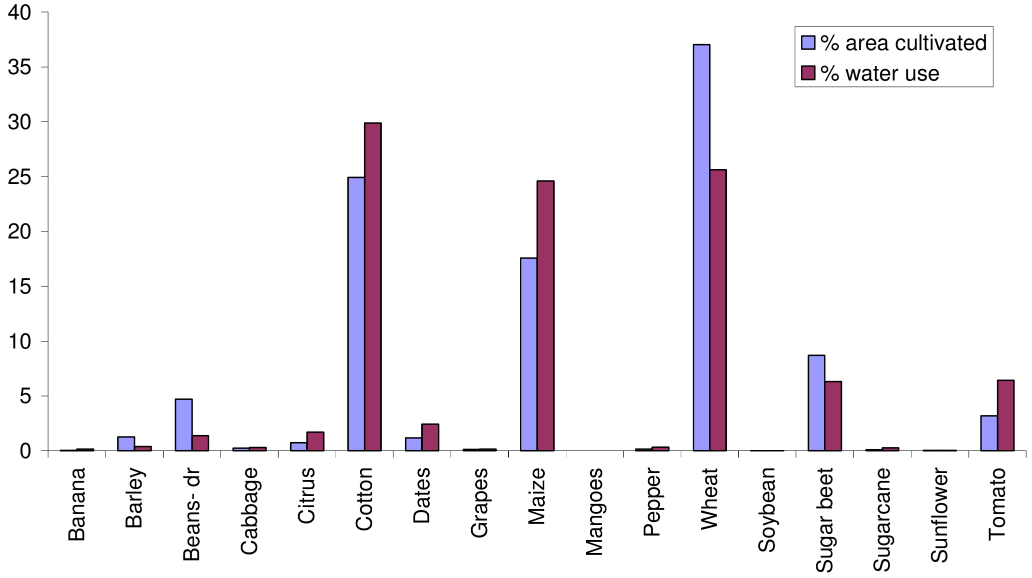
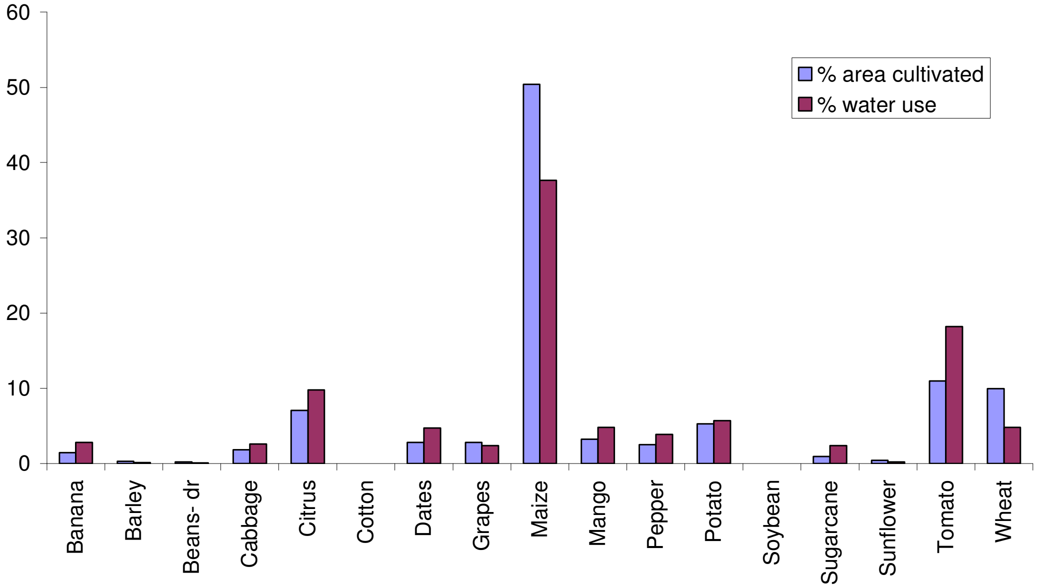


Figure 6: Rainfall versus actual crop water use by sorghum in the selected districts in Africa

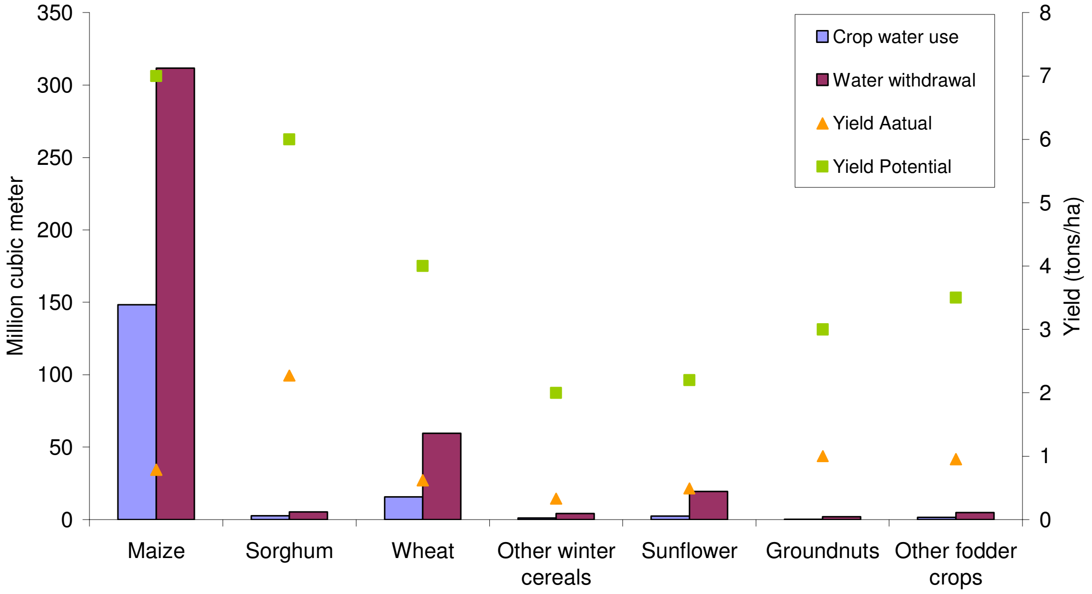


(a) Khafr el-Sheikh district

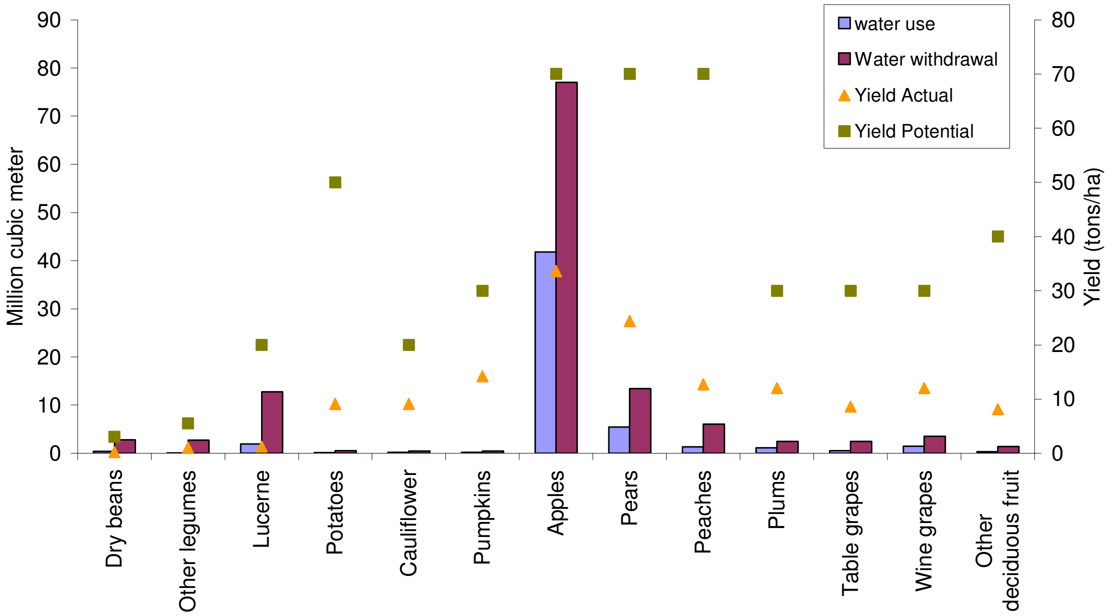


(b) Giza district

Figure 7: Area cultivated under different crops and crop water use in the selected districts in Egypt



(a) Kroonstad district



(b) Caledon district

Figure 8: Water withdrawal, water use and yield of different crops in the two selected districts in South Africa

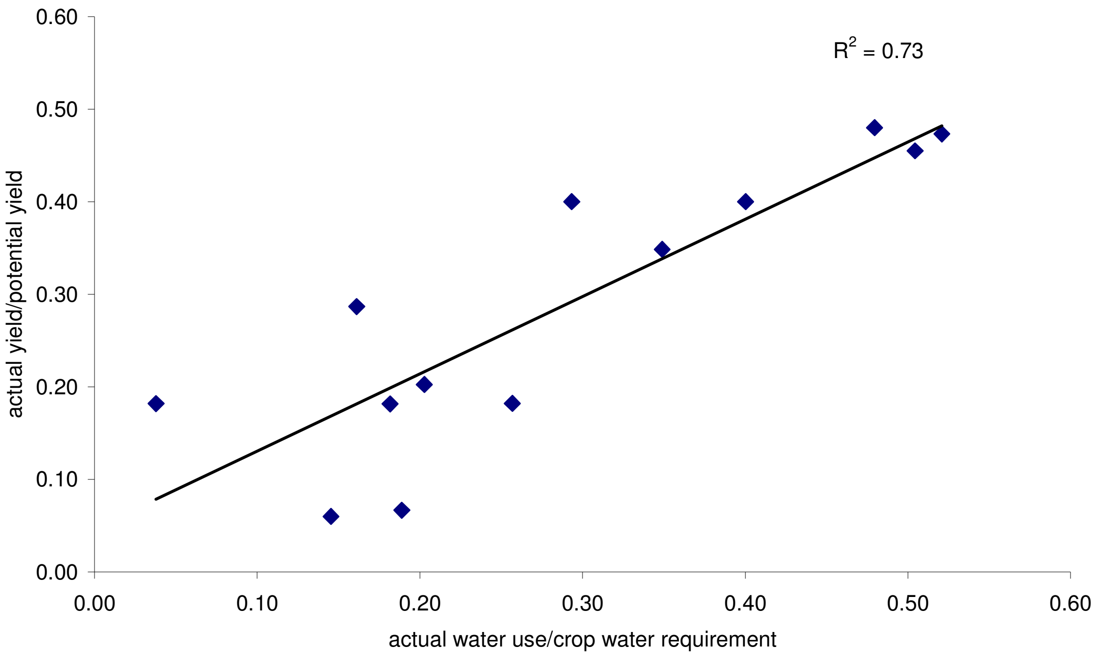


Figure 9: Water use versus yield in Caledon district in South Africa

APPENDIX 1: Using CROPWAT to study crop water requirement as effected by climate change

Background

The GEF/World Bank project “Regional climate, water and agriculture: impacts and adaptation of agro-ecological systems in Africa” seeks to investigate the effects of climate change on different agro-eco systems in Africa. The project, in its launching workshop in December 2003, adopted the Ricardian analysis to assess the economic impact of climate change on African agriculture. To further increase the understanding of the impact of climate change in agricultural production it was recommended to initiate parallel analyses in crop simulation and river basin hydrological modelling. FAO was requested to assist the national teams in the development of a unified approach in crop simulation modelling.

Initially it was planned to use crop simulation models like CERES, along with CROPWAT, for the crop simulation component of the project to study impact of climate change on crop water requirement and water stress. However the country teams, during the training workshop on “crop response simulation and river basin hydrology modelling” in Ghana, in June 2003, decided to use, solely CROPWAT for assessing future crop water requirement as effected by the climate change. This decision was based on the fact that the crop growth simulation models, although are suitable for such studies, are very data intensive and require longer training as compared to the CROPWAT programme. This issue was discussed again and the decision was reinforced by the country teams during the training workshop on “quality control for country level and regional analysis and reporting” in Egypt in November 2003.

Taking into account the concerns of the country teams, AGLW-FAO agreed to look into the possibility of outlining a methodology to use CROPWAT model for assessing the crop water requirement as effected by climate change. Since then AGLW-FAO had tried to come-up with a simple method to study the impact of climate change on crop water requirement. This note outlines the methodology and algorithms that can be used to assess the changes in the length of crop growth stages in response to changes in average temperature and Carbon dioxide concentration in the atmosphere. These “new” values of the length of crop growth stages can then be used with the climate data generated by Global Circulation Models (GCM) to compute “future” crop water requirements.

General considerations: What can and can not be studied using CROPWAT

Prospective studies on effects of Climate Change (CC) on crops, as generally considered by the International Panel on Climate Change (IPCC), may consider three different scenarios taking into account changes in (i) Climate/weather parameters (ii) climate/weather parameters plus crop physiological responses to CO_2 concentration; and (iii) climate/weather parameters plus crop adaptations.

Crops are simultaneously affected by many climatic parameters, and as a consequence, they offer an integrated response to climate change. As there are numerous interactions between parameters, and between the effects of these parameters on plants, it may seem unrealistic to identify specific single direct effects. Moreover, it may also be considered to take into account simultaneous effects, or interactions between two climatic parameters which are linked in CC and have contradictory effects on crop growth. One such example is the impact of increased level of CO_2 on crop water use: it leads to a faster establishment of LAI, then to a higher radiation interception, then to a higher potential transpiration. In the same time, higher CO_2 concentration modifies stomata closure process, which finally leads to a lower transpiration. Besides, the specific effects of these phenomena may be different for C3 and C4 crops.

CROPWAT is a generic tool that predicts crop water requirements, and crop water stress, and these will be evidently affected by climate change. It does not take into account dynamics of and interactions between different processes taking place simultaneously. Evidently, maintaining its initial simplified options, CROPWAT will not be able to take into account correctly above mentioned simultaneous and contradictory effects of climate change on crop growth and crop water requirement. This section proposes some indications on what aspects of climate change can reasonably be taken into account using the CROPWAT programme for their potential impact on the crop water requirements.

(i) Weather parameters

Purely physical phenomena (wind, radiation, rainfall, temperature and relative humidity of the air are integrated through the Penman Monteith equation for ET calculations), can be taken into account directly with CROPWAT, as input parameters. If we consider also the irrigation scheduling option of CROPWAT, rainfall pattern modifications will be taken into account directly.

(ii) Weather parameters plus crop physiological responses to CO_2 concentration

CROPWAT includes a function for estimating water stress effects on yield, through potential yields and Ky[15] coefficients (see FAO 33)[16]. CC may affect these functions on several aspects including the following:

- ***Potential Yield***: Potential yield is expected to be modified, as a result of combined effects of photosynthetic efficiency increase (due to CO_2 concentration increase), harvest index modifications, and reduction of the length of the crop cycle (due to temperature increase). Generally, as a result of these effects, the potential yield for C3 crops is expected to increase, while for C4 it is expected to decrease.
- ***Water Use Efficiency***: Another effect is a modification in water use efficiency (WUE). Increase of CO_2 concentration modifies water use efficiency and water exchanges through changes in stomatal resistance. C4 crops are more efficient than C3 in reducing transpiration with CO_2 increase. Thus, resulting in changes in Ky coefficients.

At the same time, as CC will take place gradually in the future[17], it is acknowledged here that crops, varieties, cropping systems etc. will have changed a great deal. Added to the difficulty for modifying the empirical Ky/Ymax[18] approach, we conclude that although it is possible to try and work out some algorithms for taking into account these effects. However, it would be

---

[15] Ky is a factor that describes the reduction of relative yield according to the reduction in crop water requirement (Etc) caused by soil water shortage. Ky values are crop specific and vary over the growing season according to growth stage.

[16] FAO 1979. Yield Response to Water. Doorenbos, J. and Kassam, A. H. Irrigation and Drainage Paper No 33.

[17] Climate change is a dynamic process/phenomenon and is expected to continue in the subsequent years and in future. However Climate change scenarios generally consider the time frame until 2100.

[18] Ymax is the maximum yield of a crop, which is defined as the harvested yield of a high producing variety, well-adapted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases do not limit yield.

a huge and time consuming task that may require longer time frame than the GEF/CEEPA Project life and is out of the strict scope and framework of CROPWAT. Therefore these algorithms will not be developed.

(iii) Weather parameters plus crop adaptations

CROPWAT takes into account plant physiology through an internal clock (the unit is in days), which defines the duration of phenological stages, and associates to these stages, crop coefficient values. Changes in two climatic parameters, Temperature and CO_2, will modify the growth and development engines of crops through the CROPWAT internal clock in the following manner:

a) ***Temperature:*** A certain amount of heat is required to move crops to the next development stage and for a given crop variety, this value is constant from year to year. Increasing temperature will affect the duration of the stages as far as less days will be necessary to reach the accumulated degree-day threshold. This phenomenon is not dependent on C3/C4 metabolism of a crop. Whereas temperature is not explicitly taken into account in crop development by CROPWAT, it is possible to take into account its variations as far as base and maximum temperatures (crop specific) are available. This can be taken into account with CROPWAT by assessing the length of new crop growth stages in a separate spreadsheet and then using these "new" values as input in CROPWAT. See suggested tables, algorithms and justifications in annex 1.

b) ***CO_2 concentration***: Increasing CO_2 concentration will increase the efficiency of plant biomass engine, i.e., conversion of radiation to biomass, and thus will induce faster rate of LAI[19] and Kc[20] before reaching maximum. This phenomenon is C3/C4 dependant and some theoretical development is proposed for taking it into account (see annex II). Varying CO_2 concentration also has numerous direct and indirect effects on crop growth. Many of them are linked to temperature modifications, and earlier studies considering these effects on entire plants have some difficulties in separating their combined effects or in other words to "decouple" these effects. Thus, it is suggested here to take into account only the effect on the changes in the length of growth stages during the initial and development phases of a crop. This will be realised through a) starting the development phase earlier, thus resulting in a shorter initial stage; and b) increasing Kc rate according to LAI growth modifications, hence resulting in a steeper slope. These calculations will also be done in a spreadsheet outside CROPWAT. The values obtained for lengths of initial and development phases will then be used as input in CROPWAT. See suggested tables, algorithms and justification in annex II

The combined effect of these two parameters (a & b) is described in Annex III.

NOTE: **It is worth noting here that the algorithms suggested in the section will be implemented in the spreadsheet outside CROPWAT and the results/values obtained from these algorithms will be used as input in CROPWAT.**

---

[19] LAI is not a CROPWAT variable, but Kc may be considered as statistically linked to LAI.

[20] Kc is a crop coefficient, and is a dimensionless number. Kc tells how much water a crop uses in comparison to the reference crop. For example, Kc = 1.1 means that at the particular crop stage under consideration, a crop uses 10% more water as does the reference crop.

Annex 1: Impact of increased Temperature on the duration of crop stages

The phenomenon. Crops have an internal clock based on which all the phenological stages duration are governed. Growing degree days, or GDDs, are used to estimate the development of plants during the growing season, which is closely related to the daily accumulation of heat. A certain amount of heat is required for a crop to move to the next development stage, and for a given crop variety, this value is constant from year to year. Each crop has a minimum base temperature (Tbase) or threshold below which development does not occur.

To calculate GDD, the base temperature is subtracted from the mean temperature for the day to give a daily GDD.

$$DailyGDD = (T_{average} - T_{base})$$

Where

$$T_{average} = \frac{(T_{\max} - T_{\min})}{2}$$

Each daily GDD is then accumulated over the growing season. Data bases can be found in the literature, which give precise information for GDD thresholds, considering every crop/variety and every development stage.

In tropical conditions, the suggested method is not so effective, because very hot temperatures do not provide efficient conditions for crop growth. Moreover, high night temperatures may have a negative effect on crop growth. However, these phenomena are not well described in the literature. Crop growth simulation models generally consider a threshold temperature (Tdmax) for every crop over which additional degrees are not effective anymore:

For GDD calculation, we may consider that

If $T_{average} > T_{d\max}$

then $T_{average} = T_{d\max}$

Where Tdmax is the upper threshold.

The maximum average temperature (Tdmax) for the growth of most crops ranges between 25 and 40 °C.

With CC and global warming, it is expected that daily GDD will increase, and thus the thresholds will be reached in less time. So, a reduction is expected in the duration of every crop growth stage.

CROPWAT does not calculate GDD, and does not consider inter-annual variability of stages duration. We propose here a simplified method for linking temperature increase with the reduction of stage duration.

Step 1: Quantification of the effects of increasing temperature

If D0 is the normal present duration of a crop growth stage (as used in CROPWAT), it is (indirectly) based on an accumulated sum of GDD $(\Delta GDD)_0$ so that if $(GDD)_0$ is the theoretical average daily GDD during the stage, and D_0 is the initial length of the stage (in days),

$$\left(\sum GDD\right)_0 = D_0 \times (GDD)_0$$

If we have an increase of temperature of ΔT due to CC, we will have consequently a decrease of the number of days ΔD0, so that :

$$\left(\sum GDD\right)_0 = D_0 \times (GDD)_0 = (D_0 - \Delta D_0) \times [(GDD)_0 + \Delta T]$$

Where ΔD_0 is the decreasing number of days of the stage necessary to reach the total $(\Delta GDD)_0$.

So

$$\Delta D_0 \times (GDD)_0 = D_0 \times \Delta T - \Delta D_0 \times \Delta T$$

As $\Delta D_0 * \Delta T$ has low value, we can approximate ΔD_0 as follows:

$$\Delta D_0 = \frac{D_0 \times \Delta T}{(GDD)_0}$$

OR

$$\Delta D_0 = \frac{D_0 \Delta T}{(T_{average} - T_{base})}$$

$T_{average}$ during the stage may be obtained from local conditions
T_{base} is crop specific, and is available in the literature.
ΔD_0. is given by CC scenario.

For example, if we study possible effects of CC on maize cultivated in Paris, during grain filling, we will have following estimation for the grain filling stage:

$D_0 = 80$ days
$T_{average} =$ 22 degrees
$T_{base} =$ 6 degrees
$\Delta T =$ 2 degrees

$$\Delta D_0 = \frac{80 \times 2}{22 - 6} = 10 days$$

Hence, in Crop Data window of CROPWAT, we will reduce the duration of grain filling stage from 80 to 70 days.

Step 2: Taking into account high temperature

Preliminary remark: Most likely, the temperature will not be highly affected by CC in the tropical regions. However, and with the preoccupation of proposing realistic algorithms, we introduce here a ‘security algorithm’, CHT = Coefficient of high temperature, through a correction factor built as follows:

Let us evaluate how far will be average temperature from Tdmax after modification by CC:

$$\Delta T_{d\,\max} = T_{\max} - \left(T_{average} + \Delta T\right)$$

We consider that the lower the value of ΔTdmax, the less efficient will the supplemental degrees be. It will only be fully efficient if ΔTdmax> 5. If not, then we ‘’punish’’ the ΔD value calculated in step 1

if $\Delta T_{d\,\max} > 5$, CHT = 1.
if $0 < \Delta T_{d\,\max} < 5$ CHT = $\Delta T_{d\max}/5$
if $\Delta T_{d\,\max} <= 0$ CHT = 0

$(0 \leq CHT \leq 1)$

Finally

$$\Delta D = \Delta D_0 \times CHT$$

Example

Following table presents some examples based on data from France and Nicaragua we propose here some realistic examples:

	Maize, France	Onion, France	Maize, Nicaragua
D0	80	60	80
$T_{average}$	22	22	27
T_{base}	6	2	6
T_{dmax}	30	30	30
ΔT	2	2	2
ΔD	10	6	2

Another Example: Graphic presentation of the effect of increase in temperature by 2 °C

Crop:	Wheat
Country:	Egypt
Crop Temperatures:	
T base	4.0 °C
Tdmax	30.0 °C

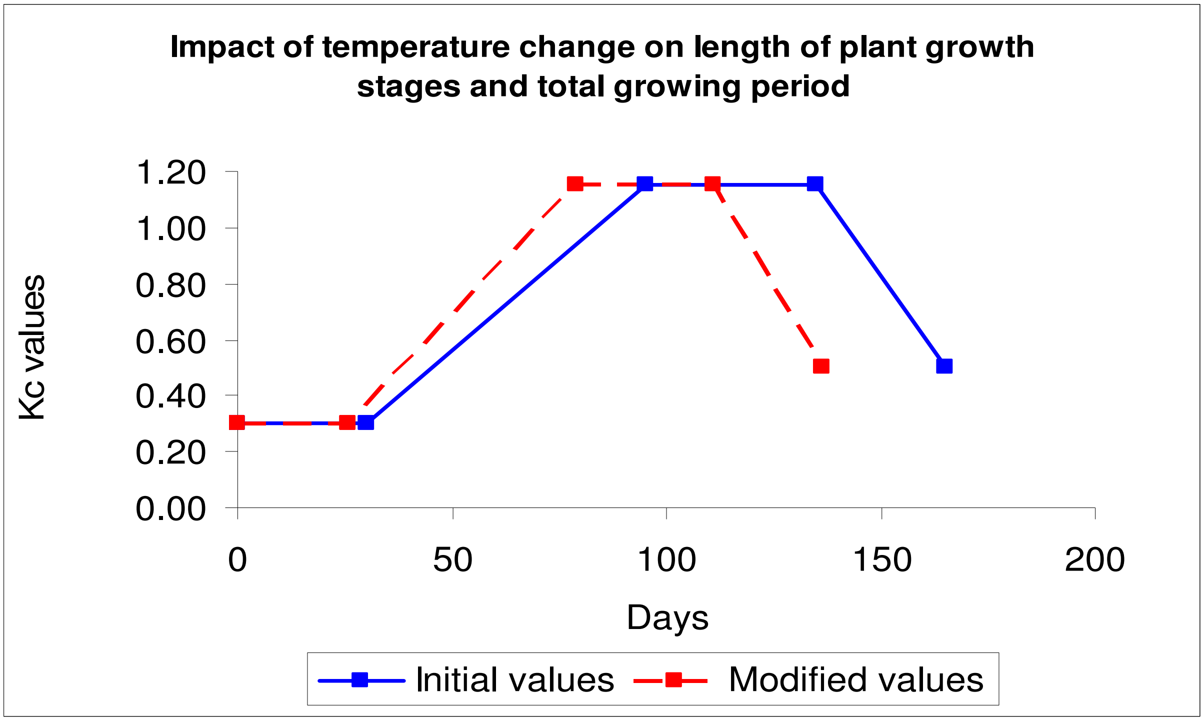
Initial/present values of crop parameters and temperature are given in the following table

Kc	values	Duration (days)	Taverage (°C)
Kc ini	0.3	30	19
Kc dev.		65	15
Kc mid	1.15	40	14
Kc end	0.5	30	17
Total		165	

With an increase in average temperature by 2 °C, the length of the growth stages will reduce and so will the total growing period as shown in the following table

Kc	values	Duration (days)	Taverage (°C)	Δ Days
Kc ini	0.3	26	21	- 4
Kc dev.		53	17	-12
Kc mid	1.15	32	16	- 8
Kc end	0.5	25	19	- 5
Total		136		-29

Following figure presents this change in the format used in CROPWAT:



Annex II: Impact of increased level CO_2 concentration on the duration of initial development and mid season crop growth stages.

The phenomenon: Increasing CO_2 concentration will increase the efficiency of plant photosynthetic engine for biomass production. It is commonly admitted that with 100 % increase in CO_2 concentration (350 ppm to 700 ppm) photosynthesis efficiency in C3 crops will increase by almost 30 %. According to the projections this level of CO_2 concentration could be reached by 2100. This increased photosynthesis is expected to lead to faster growth rate which will eventually result in crop achieving maximum LAI in relatively shorter time. Based on the literature review, we assume that for C4 crops, this phenomenon is not significant.

For taking into account the increased photosynthesis efficiency in C3 crops with CROPWAT we assume that the crop is grown under optimal conditions with neither water nor nitrogen stress.

FAO 56[21] proposes the following equation for equivalence between Kc and LAI during the first growing stage of crops:

$$Kc = Kc\,\min + (Kc\,\max - Kc\,\min)[1 - \exp(-0.7 \times LAI)]$$

(equation 97 in FAO 56)

From this equation, we estimate that Kcmax will be reached when LAI = 3

The first stages for LAI as a function of time are described with the following logistic curve, with three parameters:

$$LAI = LA\,\mathrm{Im}ax \times \left[\frac{1}{[1 + \{Exp(\alpha \times (Time - T\inf l))\}]}\right]$$

Where

LAI_{max}: is the initial maximum leaf area index and is linked with Kc through the empirical formula, derived from equation 9[7] in FAO 56. It is dimensionless (-)

Time: is the running time, in days (d)

α: is a shape parameter (the default value taken of α = -0.1 (d-1), not varying with CO_2 increase

T_{infl}: is the number of days at which the logistic curve has an inflexion point. In order to maintain coherence in the LAI curve, Tinfl is linked with LAImax and Kcmax and the duration of the growing phase (Dini + Ddev)[22] as follows:

---

[21] Richard G. A.; Pereira, L.S.; Raes, D.; Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No 56.

$$T\inf l = \left(Dini + Ddev\right) - Log\left[\frac{\left({}^{LA\,\mathrm{Im}\,ax}\!\big/_{3-1}\right)}{Kc\max}\right]$$

LAImax0 is not a CROPWAT variable. However, it is linked here with Kcmax through the following empirical relationship:

$$LA\,\mathrm{Im}\,ax = \left(3\right)^{\left(Kc\max + 0.2\right)}$$

As we know from the literature, higher conversion efficiency will result in faster biomass accumulation which resultantly will have an increase rate of LAI. It is assumed here that the increase in conversion efficiency is linearly related to the biomass accumulation. Since the biomass is described in terms of volume, which is a three dimensional variable, and the LAI is described in terms of area, which is a two dimensional variable, the rate of increase in biomass and LAI can not be linear. To deduce a logical relationship between biomass and LAI we consider the following:

if Δ biomass (-) is the increasing efficiency factor due to CO_2 increase affecting biomass, then Δ LAI (-) affecting LAI is :

$$\lambda_{LAI} = \left(\lambda_{biomass}\right)^{2/3}$$

It is assumed here that CO_2 concentration modifies growth rate of LAI by modifying LAImax proportionally to the conversion efficiency factor (ΔLAI). Furthermore, it is also assumed that the total length of the crop cycle will not be affected by increased concentration levels of CO_2.

According to the modifications of the curve, the value LAI= 3 will be reached sooner:

$$\Delta Days = Log\left[\frac{\left({}^{LA\,\mathrm{Im}\,ax_0}\!\big/_{3-1}\right)}{\left({}^{LA\,\mathrm{Im}\,ax_1}\!\big/_{3-1}\right)}\right]$$

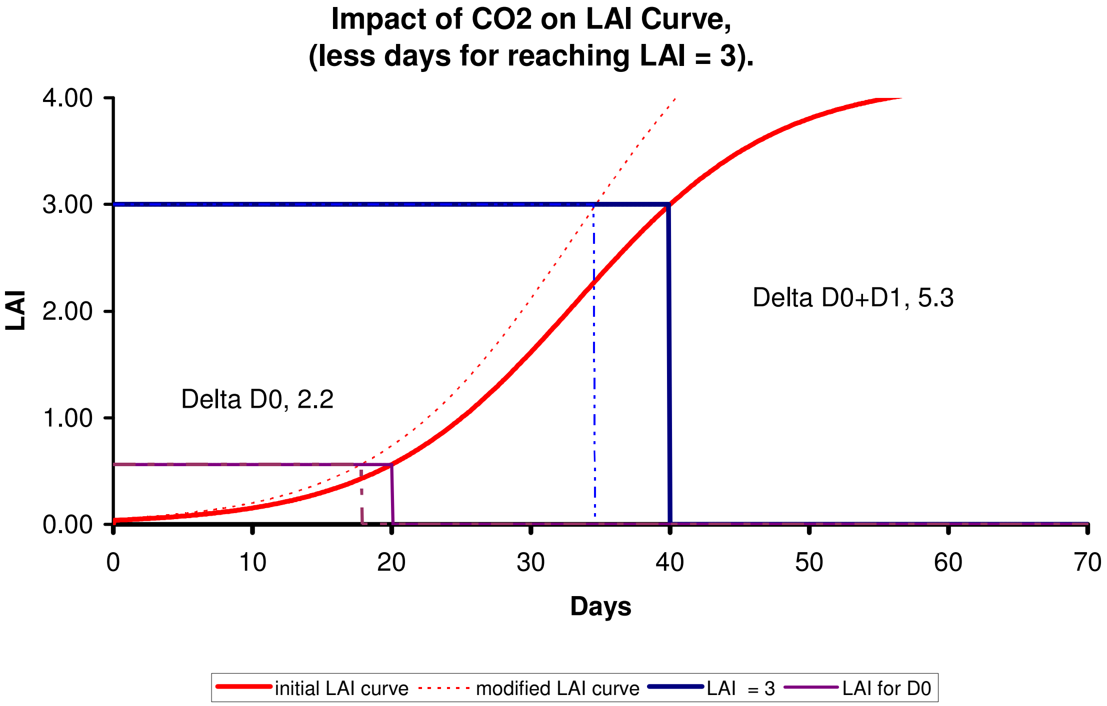
As a consequence, the initial phase will be shorter and the development phase will begin earlier. This is reached when the modified LAI equals the same value as it had reached in the former situation at the end of the initial phase. This is deduced from the LAI curve, and is calculated as follows:

---

[22] D refers to the duration (in days) of a development stage. For example Dini is the number of days a crop needs to complete its initial stage.

$$\Delta D_0 = Dini - T\inf l + \left(\frac{1}{\alpha}\right) \times \left[LN\left\{ \left(\frac{LA\operatorname{Im}ax}{LA\operatorname{Im}ax_0} \right) \times \left[1 + EXP\{\alpha \times (Dini - T\inf l)\} - 1 \right] \right\} \right]$$

The following graph presents the initial LAI curve, modified LAI curve and, as a consequence, the reduction (Delta Days) of the length of the initial and development growth stages.



Example:

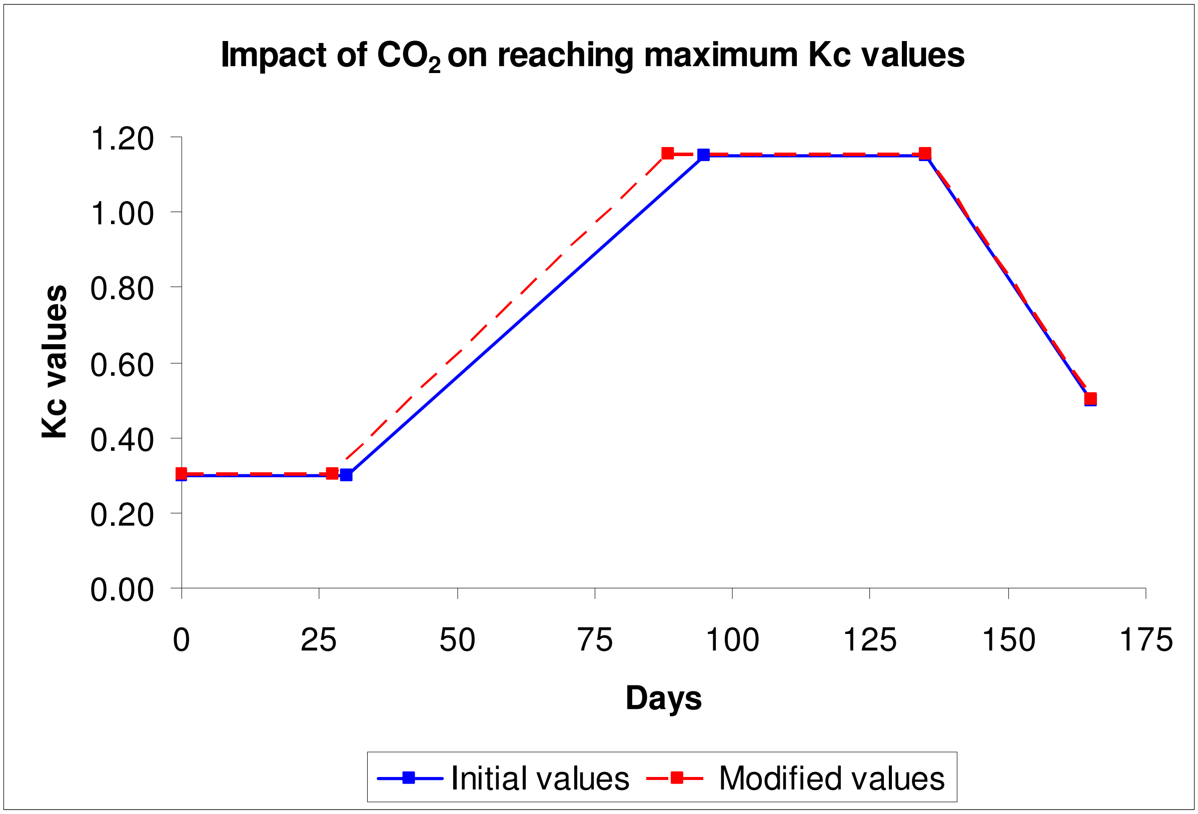
For the following values of the parameters of conversion efficiency and wheat in Egypt:

Conversion increase efficiency factor			D_0= 1.3		
LAI_{max0}	=	4.4			
Kc_{min}	=	0.3	D ini	=	30 days
			D dev	=	65 days
Kc_{max}	=	1.15	D mid	=	40 days
Kc_{end}	=	0.50	D end	=	30 days

Following values for the length of different crop growth stages are calculated:

Growth stage	Initial/present duration (days)	Modified duration (days)	Difference (Δ Days)
Dini	30	27	-3
Ddev	65	61	-4
Dmid	40	47	+7
Dend	30	30	0
Total	165	165	0

The following figure shows this change in the format used in CROPWAT



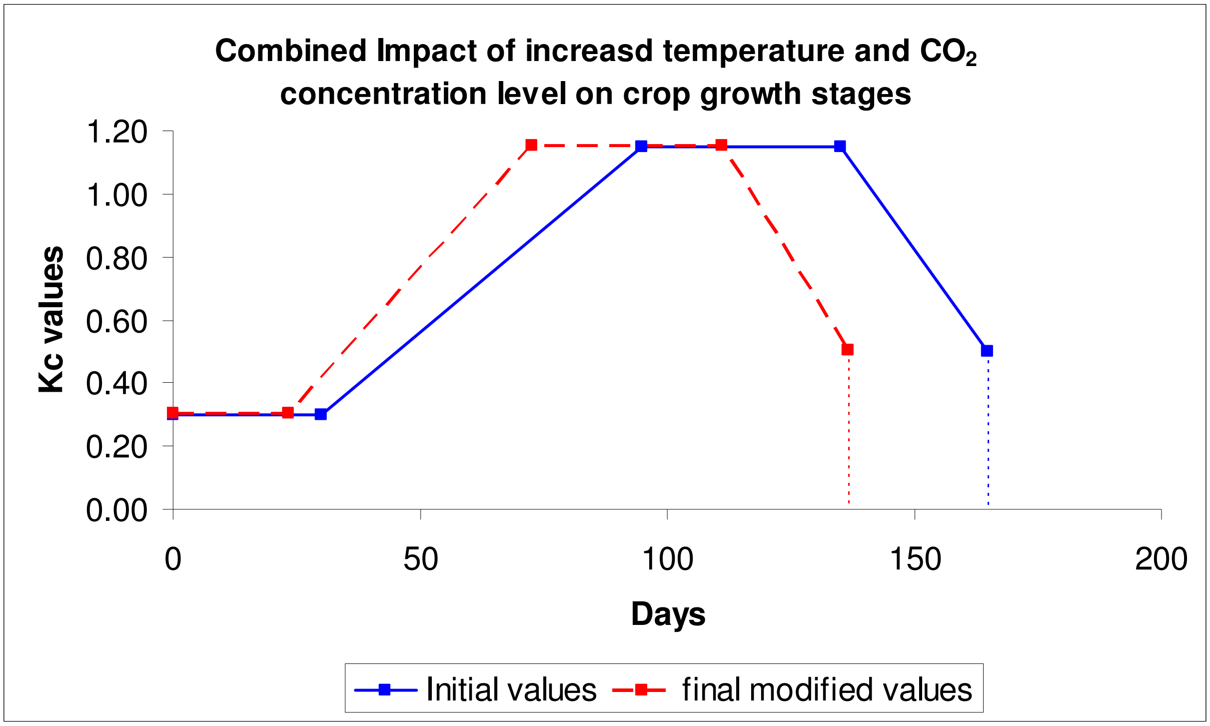
Annex III: Combining the impact of changes in Temperature and CO_2 concentration on the duration of different crop growth stages and total crop growth cycle.

To combine the effects of both temperature and CO_2 changes on the total length of a crop cycle and individual growth stages, it is proposed to simply add the total number of days reduced in each cycle.

Example: Taking the examples in Annex I and II, which demonstrate a reduction in the length of growth stages, and thus reduced total length of the crop, of Wheat in Egypt the following table shows the expected total reduction in crop growth stages.

Growth stage	**Present duration (Days)**	**Difference due to Temp. (Δ Days)**	**Difference due to CO_2 (Δ Days)**	**Total difference (Δ Days)**	**Modified duration (Days)**
Dini	30	-4	-3	-7	23
Ddev	65	-12	-4	-16	49
Dmid	40	-8	+7	-1	39
Dend	30	-5	0	-5	25
Total	165	-29	0	-29	136

The following figure shows this change in the format used in CROPWAT:



APPENDIX 2: Application of draft methodology for “using CROPWAT to study crop water requirement as effected by climate change” on Maize crop in South Africa

South Africa team used the draft Cropwat-cc methodology to study future crop water requirement and use as affected by climate change. The study was based on climate predictions[23] for the year 2050 produced by two internationally renowned institutes, the Hadley Centre (UK) and National Centre for Atmospheric Research (NCAR, USA).

Outputs from 3 General Circulation Models (GCM’s), namely Genesis - origin presently unclear, CSM - developed by NCAR, USA, and UKMO - developed by the Hadley Center, UK (termed HadCM2, a revised version of the original GCM HadCM) were used in the anaylsis.

HADCM2 scenarios were developed using two assumptions regarding sulphate aerosols, one assuming their presence and gradual decline during the simulation period, the other assuming their complete absence during the simulation period. Sulphate aerosols are a product of fossil fuel (especially coal) burning, and ironically act to reflect radiation and therefore counteract warming due to increasing carbon dioxide (CO_2). These scenarios are termed HadCM2S (with sulphate effect), and HadCM2N (sulphate effect excluded). Of the four models, Genesis tended to produce the most unique and contradictory results.

The models predict changes in temperature and CO_2 concentrations. These changes are introduced in the cropwat-cc module (see Figure A-II-1), and changes in the growth stages and total growing period of maize are derived (see table A-II-1 and Figure A-II-1). Interestingly, simulations based on data from all the models are predicting a significant reduction of the initial and development stage of maize as compared to the present situation, with minimum changes in the mid and late stages. A striking observation is that the range of projections based on the data by different models is very narrow for a district – 2 days for - Lichtenburg, 3 days for Kroonstad, and 2 days for Middelburg. The greatest decrease in the total growing period of maize (23 days less than present growing period) is projected for Middleburg district when data from CSM and HadCM2S models were used.

Based on the climate data produced by GCM and changes in the length of growth stages of maize – calculated based on draft methodology proposed by Cropwat-cc, future crop water use was determined using CROPWAT programme. Rest of the other factors, such as area grown under maize in different districts, potential and actual yield and Ky will remain constant. Results vary considerably (see table A-II-2) depending on the climate change scenario. It is striking to see that scenario based on the data from HadCM2N in Lichtenburg district is projecting an increase in crop water requirement and water use of maize. Results based on the data from all other models are projecting a decrease with sharpest (12%) being in Kroonstad district by HadCM2N.

---

[23] These predictions assume an increase in atmospheric carbon dioxide (CO2) from about 370 ppm in the year 2000 to 550 ppm in 2050.

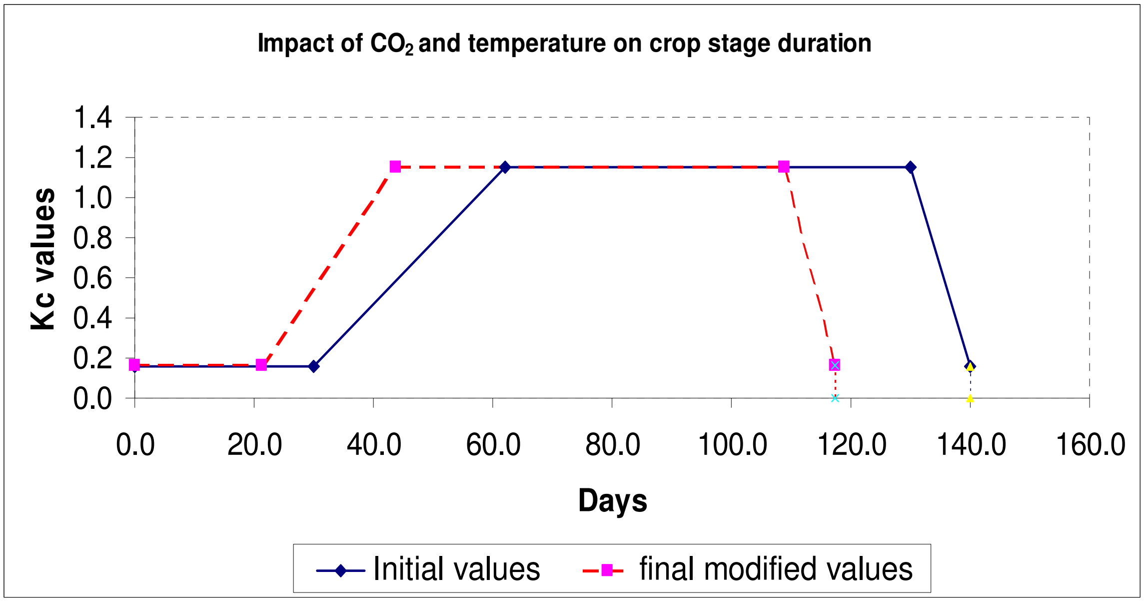


Figure A-II-1: Combined impact of changes in CO_2 concentration and temperature on growth stages of maize.

This prototype exercise shows what kind of prospective considerations can be done with the suggested methodology. Evidently, the results have to be analysed very carefully. It would be optimum to use them in a training session, in which the effects of different scenarios could be simulated and discussed with the participants.

Table A-II-1: Length of growth development stages for maize for four climate change scenarios for Lichtenburg, Kroonstad and Middelburg districts

Growth stage	**Original**	**Lichtenburg**				**Kroonstad**				**Middelburg**			
		CSM	GEN	Had CM2N	Had CM2S	CSM	GEN	Had CM2N	Had CM2S	CSM	GEN	Had CM2N	Had CM2S
D ini	30	23	23	23	23	22	23	22	22	21	22	22	21
D dev	32	24	24	24	24	24	24	23	24	22	23	23	22
D mid	68	67	67	67	67	67	67	66	67	65	65	66	65
D end	10	9	9	9	9	9	9	8	9	8	9	9	8
Total	140	122	122	124	123	122	122	120	122	117	118	119	117

Kc_{ini} 0.16
Kc_{mid} 1.15
Kc_{end} 0.16
T_{base} 8°C
Td_{max} 34°C

Relative increase in CO_2 concentration	2.0
CC Delta T	2.0

Table A-II-2: Area (ha), crop evapotranspiration (cubic m/ha), effective rainfall (cubic m/ha) and total water withdrawn (cubic km) for the three districts and four climate change scenarios using the adapted maize development phases.

District	Climate change scenario	ETo (mm)	ETcrop (mm)	Ky	Ya (t)*	Ym (t)	Ks	Area (ha)	ETcrop Actual (mm)	c (
Lichtenburg	Original	545	423	1.25	2.17	7	0.45	239750	189	4
	CSM	499	406	1.25	2.17	7	0.45	239750	182	4
	GEN	504	409	1.25	2.17	7	0.45	239750	183	4
	HadCM2N	528	433	1.25	2.17	7	0.45	239750	194	4
	HadCM2S	511	418	1.25	2.17	7	0.45	239750	187	4
Kroonstad	Original	531	416	1.25	2.7	7	0.51	130718	212	2
	CSM	480	396	1.25	2.7	7	0.51	130718	201	2
	GEN	491	402	1.25	2.7	7	0.51	130718	205	2
	HadCM2N	447	367	1.25	2.7	7	0.51	130718	187	2
	HadCM2S	490	406	1.25	2.7	7	0.51	130718	206	2
Middelburg	Original	462	353	1.25	2.91	7	0.53	88805	188	1
	CSM	404	330	1.25	2.91	7	0.53	88805	176	1
	GEN	421	339	1.25	2.91	7	0.53	88805	181	1
	HadCM2N	431	349	1.25	2.91	7	0.53	88805	186	1
	HadCM2S	407	335	1.25	2.91	7	0.53	88805	178	1
Provincial average for 5 years										