# Modeling the impact of midcentury climate change to crop yield in Mozambique: effect of rise in temperature, ground-level ozone and atmospheric $CO_2$; a layer approach

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## Abstract

This work is part of the INGC - Project "*Responding to Climate Change in Mozambique*" - theme 6 - Phase II. A layer approach is presented to evaluate and combine the effects of up to 6°C temperature rise and increases of up to 60 ppb ground-level ozone and up to 300 ppm atmospheric $CO_2$ on actual average crop yield of six selected crops: cassava, cotton, ground nut, maize, sorghum and soybean in Mozambique. Individual and combined outcome on crop yield change of 550 ppm atmospheric $CO_2$, 1.7 to 2.4°C temperature increase and 15 to 30 ppb ground-level ozone increase, as associated with Mozambique´s midcentury climate change, is calculated.

Actual modeling tends to apply a threshold value for ozone, underestimate the yield suppressing effect of ground-level ozone, overestimate 'the feeding effect' of $CO_2$ and apply traditional $Q_{10}$ temperature responses derived from short term (hours) measurements in mature organisms [27][28][29][32][48]. Here, a new approach is presented as to how temperature, ground-level ozone and $CO_2$ interactively modulate yield-outcome. To elucidate the factors that determine actual and future yield gaps, we principally combine the findings of three research teams: (1) the work on $CO_2$ – ground-level ozone interaction on crop yield of the USDA research team led by Prof. Dr. Edwin Fiscus, (2) the work on Carbon Use Efficiency (CUE) of Prof. Dr. Marc van Iersel and colleagues at the Georgia and Utah State University and (3) the work on ozone modulated epigenetic memory effects and the recent discovery in this area by Crops Advance Brazil [48], showing:

(1) the end of a paradigm: extra atmospheric $CO_2$ basically does not feed crops but acts as an oxidative stress 'detox', especially relevant to oxidative stress caused by ground-level ozone,
(2) the CUE paradox: crops' Carbon Use Efficiency tends to be a fixed ratio; even so it can be significantly influenced and as opposed to short term changes, long term temperature change hardly interferes with CUE,
(3) the CUE paradox explained: crops in their juvenile phase memorize and subsequently permanently fix their respirational efficiency. This process is modulated by oxidative stress during the crops' juvenile phase.

Yield is basically modulated by oxidative stress caused by ground-level ozone as opposed to being modulated by atmospheric $CO_2$ and there is no threshold or 'safe value' for ozone exposure.

Ground-level ozone generates a *false* signal of metabolic perturbation; ozone exposure during the juvenile phase of a crop limits the maximum attainable yield.

## Introduction

The purpose of this paper is to predict the influence of climate change, as reflected by the change of three major climate factors i.e. temperature, ground-level ozone and atmospheric $CO_2$, on actual and future crop yields in Mozambique and to outline possible measures to mitigate negative effects on yield.

As part of the 'Theme 6 contribution' to Phase II of the Mozambican National Institute for Disaster Management (INGC) Project "*Responding to Climate Change in Mozambique*", the present analysis addresses the rationale and mathematical approach for modeling the effects of increases of *temperature, ground-level ozone and atmospheric CO2* on crop yield.

INGC Phase I recommended that additional crop modeling is required to improve the robustness of findings of yield changes resulting from climate change [1]. Phase II therefore continued the analysis, applying all seven instead of the initially selected three Global Climate Models (GCMs) [ref. 1, p.21, Table 1.10] as well as a new calibrated crop model (Clicrop) for the six selected crops: cassava, cotton, ground nut, maize, sorghum and soybean. Phase I and initially also Phase II isolated the combined effect of water availability and temperature on *crop transpiration* as the main restricting factor to yield.

In the course of researching and developing Phase II, it was recognized that under changing climate, crop Carbon Use Efficiency (CUE), that is the carbon sequestered or the Net Primary Production (NPP), as percentage of the total carbon initially captured in the overall process of photosynthesis, i.e. Gross Primary Production (GPP), can no longer be considered a constant physiological ratio. Subject to temperature rise and ground-level ozone rise, both photosynthesis (NPP, $PS_{brutto}$) and respiration (R) should be expected to readjust (NPP↓, R↑) and as will be shown, to the extent that rising atmospheric carbon dioxide content, through its 'feeding effect', in general cannot compensate for the negative effects of respiration and photosynthesis on yield.

$$NPP = GPP - R \qquad \text{(Formula 1)}$$

$$CUE = \frac{NPP}{GPP} \qquad \text{(Formula 2)}$$

Changes in CUE have a direct and potentially high impact on crop yield as formula 3 below shows for the initial exponential growing phase. $P_{(d)}$ = accumulated production at day (d) expressed as gram Carbon (gC), IG = initial weight (gC), $PS_{brutto}$ = gross photosynthesis ($gC.gC^{-1}.d^{-1}$), CUE = Carbon Use Efficiency.

$$P_{(d)} = IG \times e^{(PS_{brutto} \times CUE \times d)} \qquad \text{(Formula 3)}$$

Other studies confirm that temperature changes have strong impact on yields [2][6][7][8][9][13][14][24][30][32]. Lobell & Burke [17] conclude that progress in understanding crop responses to temperature and the magnitude of regional temperature changes are two of the most important needs for climate change impact assessments and adaptation efforts for agriculture. The European Environment Agency additionally identifies ground-level ozone as a factor projected to have significant negative impacts on agriculture [16][20].

Furthermore, timing of seasonal events or the phenological response of crops is, next to day-length, principally triggered by temperature. Temperature increase can extend a by low temperature limited growing season. This is potentially beneficial to season's yield as the growing season is the farmer's window in which to produce. On the other hand the crop cycle, i.e. the plant's window in which to produce, strongly correlates positively with yield and tends to be reduced with increased temperatures, thus reducing yield. Data from Quadir et al. [6] for example show that for sunflower production every 1$^{o}$C average temperature increase reduces the crop cycle with 9.3 days, reducing yield by 5.7%, compared to optimum yield realized. Thus, for annual crops, on single planting basis, temperature increase is associated with shortened crop cycle and yield reduction. Where and when applicable, adaptive measures therefore include advancing of the agricultural calendar, influencing day-length. This most likely involves selecting suitable varieties [15][16]. Yield response to temperature change of perennial crops like cassava, having a crop-cycle of more than one year, will be approached differently (see perennials, page 8).

It was therefore decided to further improve our modeling by including *temperature* and *ground- level ozone* as separate factors.

**It should be noted that in the following simulations, relating the influence of the weather components rainfall, temperature & ground-level ozone, individually or in combination, to crop growth and yield, all other factors that may influence growth, including factors like farm management and socioeconomic factors, are assumed to remain constant.**

For our modeling approach the key-word is "change", which results in technical modeling benefits. The actual yield data serve as the basis that reflects and confirms the actual influence of *all factors involved*. Yield change per each changing factor (keeping all other factors constant) is simulated on the basis of changes in the eco-physiological processes that are considered to be relevant.

(1) phenological development,
(2) transpiration,
(3) $CO_2$ assimilation,
(4) respiration,
(5) dry matter formation,
(6) partitioning of assimilates to the harvestable organs.

The here considered six crops of interest are: cassava, cotton, ground nut, maize, sorghum and soybean.

- **Base map – Actual yields**

  From phase I, six maps, one per crop, showing actual average annual yields are used [1].

  Using the actual yield data of the six crops of interest as point of departure greatly simplifies the model as it can be restricted solely to the dynamics of yield change influenced by change of each individual factor.

In *a layer approach*, next to transpiration (layer 1), we add temperature (layer 2), ground-level ozone (layer 3) and atmospheric $CO_2$ (layer 4) individually, making it possible to superimpose them individually as well as in combination on *the base maps, per map giving the present actual average annual yield per culture* in Mozambique.

The layer approach also offers practical benefits: it facilitates the evaluation of the impact of the individual factors in their contribution to yield change. This will help prioritize adaptive measures that focus on mitigating the effect of rainfall, temperature changes and ground-level ozone on the actual potential yield of crops.

- **Layer one – Transpiration**

  In phase I, two forms of presentation per crop are given, one showing projected yield & the other showing yield change, due to transpiration change [1].

  In phase II, rainfall & temperature change have been predicted by applying all seven Global Climate Models from phase I [1]. The combined effects of rainfall & temperature change on transpiration have been predicted by applying the calibrated crop model *Clicrop*. Linking the combined effects on $CO_2$ assimilation, dry matter formation & partitioning of assimilates to the harvestable organs predicts the relation between transpiration change and yield change. These results are presented in a separate document but the general outcome confirms the outcome as presented in phase I and indicates that at this sub-level little change is to be expected on Mozambique's national level.

- **Layer two – Temperature**

For annual crops the followed approach is epidemiological; per crop the historical temperature is correlated to yield event patterns, without explaining the underlying physics or trying to feed a multiple variable model.

- **Layer three – Ground-level ozone**

  Showing yield change from predicted relative yield change due to ground-level ozone change.

- **Layer four – Atmospheric $CO_2$**

  Showing yield change from predicted relative yield change due to atmospheric $CO_2$ change and as under Quantitative analyses will be shown, cannot be separated from the ground-level ozone level.

## Quantitative analysis

- **Temperature rise - yield *change* related to general temperature *change***
- **Ground-level ozone rise - yield *change* related to general ground-level ozone *change***
- **Atmospheric $CO_2$ rise - yield *change* related to general atmospheric $CO_2$ *change***

(Observation: The period is used as the decimal mark).

### 1. Temperature rise - yield change related to general temperature change

Crop growth and yield correlate positive and linear with accumulated heat during the growing season [6][7][8][14][15][16]. For non-perennial crops, Growing Degree Days (GDD) is a simple mathematical expression for the heat accumulation and a modeling tool to help predict plant developmental progress along the crops cycle as will be explained below [6][7][8][14][15][16]. For perennial crops, see paragraph "perennials" at page 8. The crops cycle or number of days between planting and harvest reflects the time for the crop to accumulate carbon, i.e. its time-window to come to yield. The crop cycle is not only crop and variety depending but is also a function of temperature. When, for the same planting-date, the climate tends to be slightly hotter, the crop cycle tends to be shorter [16]. It was found that a substantial data base should be used for the analyses to get a good impression of this effect, combining data of various plantings with varying planting dates. An example of the possible outcome is formula (1) at page 6: Crop cycle (days) = -9.34 × average daily GDD ($^{o}$C) + 264. Comparing only two plantings that have their day of planting in different seasons may give the false impression that the crop cycle is longer when temperatures are higher, i.e. the opposite of the real effect. This is so because it also is *the distribution of heat along the crops cycle* that strongly defines cycle length and yield-outcome.

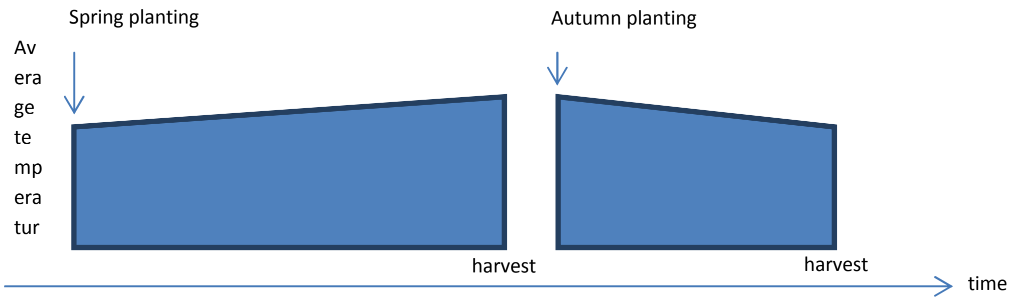

Figure 1. Distribution of heat along the crop cycle strongly defines cycle length & yield-outcome.

The influence of temperature on the partitioning of assimilates to the roots, stems, leaves and the storage organs is a function of the developmental stage of the crop [15]. A spring planting, having a relatively cool start at planting and building-up to a relatively hot finish at harvest is likely to give the longest crop cycle with the highest accumulated GDD and the highest yield-outcome. The opposite goes for an autumn planting [6][23]. For example, by integrating data form Quadir et al. [6] for sunflower when expressing the temperature distribution (TD) by $T_{amp}$ / $T_{amh}$ , whereby $T_{amp}$ = average temperature of month of planting and $T_{amh}$ = average temperature of month of harvest, for TD we find a range of 0.5 to 1.8 inversely and linearly correlating with cycle length (n=8, $R^2$=0.88), GDD (n=8, $R^2$=0.95) & yield (n=8, $R^2$=0.95).

GDD therefore encompasses <u>three inter-dependent variables</u>:

(1) <u>The temperature</u>, expressed as average above threshold or base temperature ($T_b$) of maximum and minimum daily temperature ($T_{max}$ & $T_{min}$):

$$GDD = \sum_{i=l}^{n} \left( \frac{T\max + T\min}{2} - Tb \right) \qquad \text{(formula 4)}$$

, that is a measure for the effectively accumulated heat that contributed to the development and growth to yield of the crop along its cycle,

(2) <u>The gradient of temperature distribution</u> along the crops cycle,
(3) <u>The number of growing days</u> between planting and harvest that is the actual crop cycle.

In calculating the GDD, a daily average temperature below $T_b$ is accounted for as $T_b$ to yield 0 GDD for that day. Within the practical range of temperatures up to approximately 40$^o$ C, for C3 as opposed to C4 crops a cut-off value of for example 30$^o$C is normally applied to $T_{max}$ that is a temperature limit above which temperature is considered not to contribute any further to growth and development. For $T_{max}$ > $T_{cutoff}$, the cut-off temperature is used in calculating the GDD.

- Within the scope of this analysis it is important to realize that relative yield *reduction* due to a general temperature *rise* is the net effect of crops cycle reduction partially compensated for by daily GDD increase.

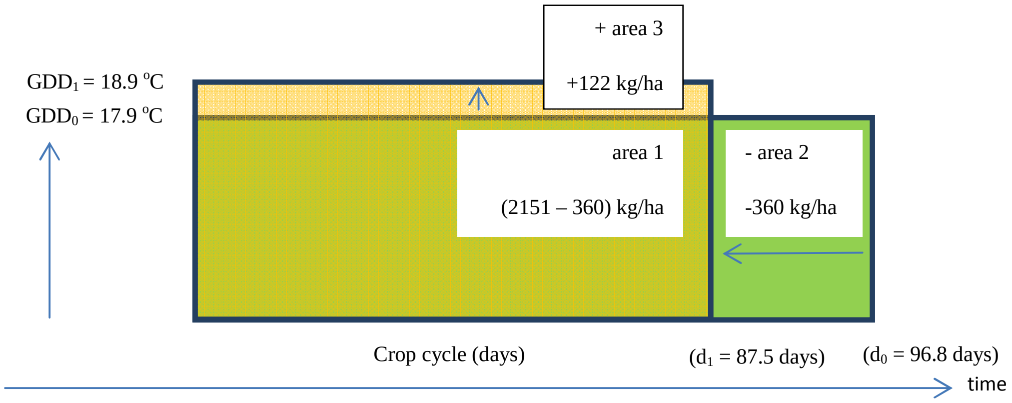

Figure 2. Yield change of sunflower due to a 1$^o$C average temp rise.

Per crop three linear relationships need to be defined: (1) crops cycle as a function of average daily GDD which will provide the crop cycle change per unit of temperature rise, (2) yield as a function of crop cycle which will provide the component of the yield reduction per unit of temperature change and (3) yield as a function of accumulated GDD which will provide the component of the yield increase per unit of temperature change. The two components of yield change have opposite signs and for temperature rise the net out-come is negative, i.e. a yield reduction. (4) Additionally, the actual average daily GDD needs to be determined.

For example, by integrating data form Quadir et al. [6] for sunflower we find (1)→(2)→(4)→(3):

(1) Crop cycle (days) = **-9.34** × average daily GDD (°C) + 264
(2) Yield (kg/ha) = **38.5** × crop cycle (days) – 1591

- The component of the yield change per unit of temperature change = -9.34 × 38.5 = -360 kg/ha per +1°C increase.

(4) Actual average daily GDD = **17.9 °C** → in (1) gives actual Crop cycle = 96.8 days.

(3) Yield (kg/ha) = **2,72** × total accumulated GDD (°C) - 2562

- New crop cycle = 96.8 – 9.34 = 87.5 days with +1°C GDD per day extra = accumulated 87.5 °C extra → (3) 87.5 × 2.72 = +238 kg/ha per +1°C increase.
- Net to yield change: -360+238 = -122 kg/ha per 1°C increase.
- Initial yield is (3) 2.72 × 17.9 × 96.8 – 2562 = 2151 kg/ha

- Relative yield change per unit of temperature change = -122/2151 = -0.057 or:
  - -5.7% per +1°C
  - Temperature change of +1.5 °C to +5.7 °C is expected to affect relative sunflower yield by -9% to -33%.

| **Sunflower** | y = ax+b | | | |
|---|---|---|---|---|
| | Y | x | A | B |
| (1) | Crop cycle (days) | Average daily GDD (°C) | -9.34 *(A)* | 264 *(B)* |
| (2) | Yield (kg/ha) | Crop cycle (days) | 38.5 *(C)* | -1591 |
| (3) | Actual average daily GDD (°C) | - | - | 17.9 *(D)* |
| (4) | Yield (kg/ha) | Total accumulated GDD (°C) | 2.72 *(E)* | -2562 *(F)* |

$$\text{Relative yield change per unit of temperature change} = \frac{AC + E\,(\,AD + B + A\,)}{ED\,(\,AD+B\,) + F} \times 100\% = -5{,}7\ \%\ (^{o}C^{-1})$$

Table 1. The calculation of relative yield change per unit of temperature change.

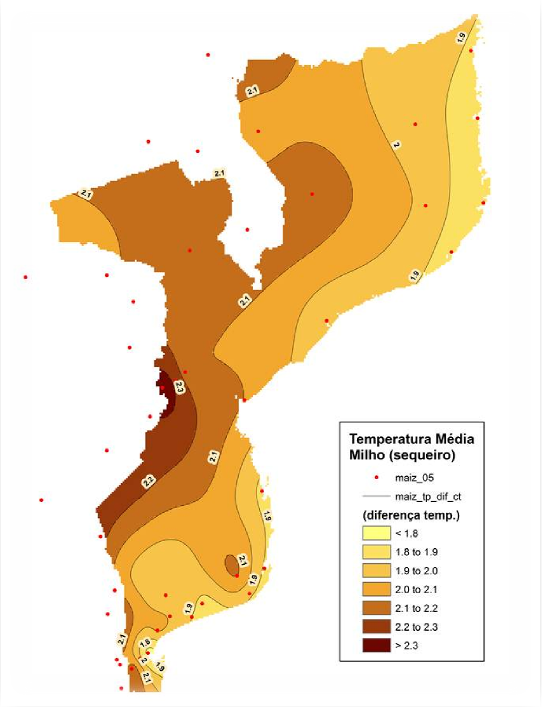

Figure 3. Average midcentury temperature change for the planting season (in this example for corn), ranging from 1.7 to 2.4$^{o}$C.

In the same way the relative yield change ($\Delta Y_{rel}$) due to temperature change, per unit of temperature change ($\Delta T$) can be determined and applied to the predicted range of +1.7$^{o}$C to +2.4$^{o}$C for average midcentury planting season's temperature change:

| Crop | Relative yield* change per temperature change ($\Delta Y_{rel}/\Delta T$) | | | |
|---|---|---|---|---|
| | Unit +1$^{o}$ C | +1.7$^{o}$ C | Mean +2.1$^{o}$C | +2.4$^{o}$ C |
| Sunflower | -5.7% | -9.7% | -11.7% | -13.7% |
| Groundnut | -5.0% | -8.5% | -10.3% | -12.0% |
| Maize | -6.1% | -10.4% | -12.5% | -14.6% |
| Sorghum | -4.7% | -8.0% | -9.6% | -11.3% |
| Median | **-5.4%** | -9.1% | -11.0% | -12.9% |
| Cassava** | +2.9% | +4.9% | +5.9% | +7.0% |
| Soybean*** | -5.4% | | | |
| Cotton*** | -5.4% | | | |

Table 2. Relative yield change per unit of temperature change for selected crops.

* Observation 1: "Yield" refers in principle to yield per crop cycle. If, under the assumption as put forward at page 3, the crop calendars do not change, the percentage of yield change also applies to yield in general, e.g. per season or per year.

** Observation 2: The logic as summarized in table 1 does not apply to perennial crops like cassava. For the explanation see paragraph “Perennials” below.

*** For Soybean and Cotton, due to incomplete data, the average results of sunflower, groundnut, maize & sorghum have been used as indicative estimate for the influence of temperature increase on yield change.

Table 2 summarizes the predicted yield changes under the assumption as put forward in bold at page 3 **that nothing changes but the average temperature**. By for instance jointly assuming a backward shift in time of the planting calendar, yield reduction can be alleviated and numbers will become more positive, potentially giving a false impression of the effect of temperature on yield. This may happen especially when the numbers start a life of their own without proper reference to their underlying basic assumptions.

For a *projected local average temperature change* ($\Delta T_{p.avg.local}$) of the actual local average temperature, the *projected* local average relative yield is: $Y_{p.avg.rel.local} = ( 1 - ( \Delta Y_{rel}/\Delta T \times \Delta T_{p.avg.local}))$. This is relative to local actual average absolute yield ($Y_{a.avg.abs.local}$) so in absolute terms the *projected* local average absolute yield becomes: $Y_a \times Y_{p.rel.local}$.

Example: [Ref. 1, main report INGC, table 4.2, p.101] Sunflower average yield 2006-2007 = 0.5 to 1.5 t/ha. For the projected midcentury average temperature change of +1.5 to +5.7$^{o}$C the average yield will consequently suffer a -9% to a -32% change. Relative yield will be 91% to 68% of actual yield.

Sunflower **actual** average yield expectancy = 0.5 to 1.5 t/ha.

- Projected midcentury absolute yield becomes ‘**best case**’ (95% probability to be worse): 0.5 × 91% to 1.5 × 91% = 0.5 to 1.4 t/ha.
- Projected midcentury absolute yield becomes ‘**average case**’ (50% probability to be worse): 0.5 × 80% to 1.5 × 80% = 0.4 to 1.2 t/ha.
- Projected midcentury absolute yield becomes ‘**worst case**’ (5% probability to be worse): 0.5 × 68% to 1.5 × 68% = 0.3 to 1.0 t/ha.

## Perennials

Perennial crops like cassava are plants that by nature live for more than two years. As opposed to annual crops like sunflower or groundnut, the perennial life-cycle is not restricted to a temperature dependent window of generally 3 to 4.5 months with a, for the farmer to assert, ideal date of planting with a view to maximize yield-outcome. Some perennials like cassava are ‘evergreens’, carrying leaves and sequestering carbon year round. The approach of estimating average yield change as a function of average temperature increase by influencing cycle reduction is not applicable to perennials.

## Cassava

Cassava is a perennial evergreen and chilling-intolerant crop. It is rare to see cassava survive in areas with minimum temperatures of 15$^{o}$C or less. Temperatures below 20$^{o}$C close stomata of cassava. High temperatures up to approximately 30$^{o}$C tend to open them [24]. Low temperatures provoke excessive levels of oxidative stress as is reflected by the stomatal behavior in relation to temperature [25]. The phytohormone abscisic acid (ABA) induces stomatal closure by inducing hydrogen peroxide ($H_2O_2$) production and both ABA & $H_2O_2$ inducing nitric oxide (NO) production by the enzyme nitrate reductase (NR). It is the NO signal that induces stomatal closure (with or without $H_2O_2$) [25]. As $H_2O_2$ induces NO production, it is our rationale that the ‘false $H_2O_2$ signal’ from ozone is a trigger for the observed ozone induced stomatal closure [50].

### Modeling atmospheric temperature increase versus change of actual yield

For the purpose of modeling the impact of **temperature rise** on actual yield, the selected crops have been divided into annuals (cotton, ground nut, maize, sorghum and soybean) and perennial (cassava). Under temperature rise, annual-crops' yield principally suffers from *crop cycle shortening*. Although increasing temperatures raise the daily accumulated growing degrees (GDD), which in general is associated with yield increase, overall yield is reduced due to the stronger effect of crop cycle reduction on yield.

- For **annual crops** on average, our calculations show the combined outcome of GDD increase and crop cycle reduction on yield to be 5% yield reduction for every $1^{o}$C of average temperature increase.

The perennial cassava is both C3 and C4, an evergreen and due to average temperature increase expected to have its yield on average increased, principally due to increased average minimum temperatures mitigating associated oxidative stress. The crop cycle of perennials is not expected to change under increasing temperatures and alleviation of low temperature stress is expected to contribute positively to yield-outcome.

- For **the perennial cassava**, on average a 2.9% yield increase for every $1^{o}$C average temperature increase is projected [24][30].

- The average yield ($dY_{rel}$) increase per $+1^{o}$C increase is a function of the average actual leaf temperature ($T_{leaf\text{-}avg\text{-}act}$). $T_{leaf\text{-}avg\text{-}act}$ is calculated as the average of the maximum and minimum daily leaf temperature: $T_{leaf\text{-}avg\text{-}act} = [T_{leaf\ max} + T_{leaf\ min}]/2$.
- $dY_{rel} = 0.66 \times T_{leaf\text{-}avg\text{-}act}^{-1}$.

Actual average leaf temperature can roughly be derived from the actual average air temperature minus $3^{o}$C.

### 2. Ground-level ozone rise - yield *change* related to general ground-level ozone *change*

For a given crop, past ontogenetic phase, its carbon use efficiency (CUE), defined as carbon sequestered over carbon captured, and yield seems constant and immune to temperature variation. Crops Advance's recent research results, however, show that oxidative stress, especially as caused by ground-level ozone, up-regulates the AOX relative to COX therefore making ATP production more carbon – costly, a cost that is not compensated by photosynthesis. Analyzing effects on carbon use efficiency, there are therefore three major factors to be considered and their effects to be combined:

(1) **Ozone↑** → Respiration↑ & Photosynthesis↓= CUE↓, Crop cycle↓:
Overall effect: all crops: **yield↓**
(2) **Temperature↑** → GDD↑ & Crop cycle↓, Respiration↑ & Photosynthesis ↓or↑ depending on actual temperature: Overall effect: annual crops: **yield↓**, perennials: **yield↑**
(3) **$CO_2$↑** → "Ozone-effect"↓, CUE↑: Respiration↓ & Photosynthesis↑, Leaf-temperature↑, GDD↑ & Crop cycle↑ (!), Partitioning of sequestered carbon to harvested organs↓:
Overall effect: all crops: **yield↑**

Modeling to date often applies a threshold value for ozone, underestimates the yield suppressing effect of ground-level ozone, overestimates 'the feeding effect' of $CO_2$ and applies y traditional $Q_{10}$ temperature responses derived from short term (hours) measurements in mature organisms [27][28][29][32][48]. Here, a new approach is presented as to how temperature, ground-level ozone and $CO_2$ interactively modulate yield-outcome.

A paradigm is broken by Fiscus team, teaching that the assumed 'feeding effect' of increasing atmospheric $CO_2$ in reality is principally due to *$CO_2$ counteracting the oxidative signal from ground-level ozone*. The carboxylating enzymes Rubisco and PEPC responsible for the incorporation of $CO_2$ are redox sensitive by having cysteine groups of which the oxidation state modulates the enzymes activity explaining the enzymes sensitivity to ozone induced oxidative signals, principally through hydrogen peroxide [22][33][34]. Increasing $CO_2$ favors the by β-carbonic anhydrase and superoxide dismutase (SOD) facilitated reduction of hydrogen peroxide by oxidation of NADPH [39]. For Barley, it was demonstrated that the hydrogen peroxide scavenging enzyme catalase (CAT) and SOD increased rapidly after plants were transferred from elevated $CO_2$ (700 ppm) back to ambient levels [35], offering a strong rationale for the observed 'anti ozone' effect from atmospheric $CO_2$ increase. It may therefore be concluded that the rate of carboxylation is a function of the atmospheric [$CO_2/O_3$] flux ratio into leaves. For cotton, rice, soybean, wheat, groundnut, snap bean and potato, Fiscus demonstrates that under low ozone conditions (25 ppb) a doubling of actual atmospheric $CO_2$ (372 to 706 ppb) will on average only marginally increase yield (+3%) whereas under high ozone conditions (60 ppb) a doubling of atmospheric $CO_2$ will give considerable *relative* yield increase (+35%) although in absolute terms *the yield is merely restored to its 'low ozone level' yield* (!) [27][28][29].

- **Yield is basically modulated by ground-level ozone as opposed to atmospheric $CO_2$**
- **No threshold or 'safe value' applies for ozone exposure**

A reference for data on the effects of $CO_2$ application on crop production is the Dutch research station for floriculture and glasshouse vegetables [46]. For a greenhouse crop at 372 ppm $CO_2$ and under the circumstances that only atmospheric $CO_2$ is considered the limiting factor for growth and under full light conditions their most positive projection is 25% dry matter increase for $CO_2$ increasing to 706 ppm. For every extra 100 ppm $CO_2$ on top of 706 ppm $CO_2$, projected dry matter increase is less than 4%. Using data from Fiscus' research, a 25% yield increase at 706 ppm $CO_2$ relative to *372 ppm $CO_2$ and 15 ppb ground-level ozone* is projected if the greenhouse air at 706 ppm $CO_2$ contains approximately 45 ppb ozone. Dutch greenhouse air is mostly enriched with $CO_2$ from gas combustion. Low $NO_x$ ($NO_x$ = NO + $NO_2$) equipment produces approximately 20 ppm $NO_x$ (with the alarm set at 30 ppm) at 11.7% $CO_2$. If used to maintain 706 ppm $CO_2$ in a closed greenhouse environment, this mixture supplies (volume parts) 121 ppb $NO_x$ of which 35 ppb are $NO_2$. $NO_2$ in the light dissociates to NO + ozone. 35 ppb $NO_2$ is the equivalent of 35 ppb $O_3$. If the cleaned combustion gasses contain as little as 10 ppb ozone, including 35 ppb $NO_2$ the result is 45 ppb O3 equivalent. The limit for ozone from combustion gasses in the greenhouse environment is generally set at 30 ppb [46].

So why is it that in the professional production of flowers and vegetables, the greenhouse atmosphere is enriched with $CO_2$? Basically, because in the greenhouse environment projected to keep all growing factors at their optimum, the lack of $CO_2$ (defined as below environmental concentrations, to date about 400 ppm) reduces productivity significantly. At 300 ppm $CO_2$, average productivity is reduced by 13% and at 200 ppm $CO_2$ the average reduction is about 38%. Within the objective to keep $CO_2$ at 400 ppm to feed the crop, due to the oxidative load present in the greenhouse air, the optimum concentration for $CO_2$ is about 700 ppm to largely compensate for the 'ozone effect'. Outside air in the Netherlands (as goes for the whole of Europe) for that sake is no viable alternative as (especially from April to November) during day-time the '7 hour average' is very likely to be above 35 ppb ozone [20][21][47].

Like $CO_2$, **ground-level ozone** is absorbed by all crops through the stomata. Intra-cellular, absorbed ozone is converted into hydrogen peroxide ($H_2O_2$) that acts as a diffuse intra- and inter-cellular oxidative signal. It triggers cell-protecting feedback mechanisms which includes the up-regulation of the mitochondrial alternative oxidative pathway (AOX). Electrons that are deviated from their normal cytochrome oxidative pathway (COX) into the AOX, will not contribute to further ATP generation but have their energy dissipated as heat. Cell-protecting feedback mechanisms, like the AOX, are normally activated upon oxidative stress from proper cellular metabolic perturbation. Understanding that cellular metabolic processes functionally use trans-boarding $H_2O_2$ as a signal for back-coupling to **process**

**functional** oxidative activity, it becomes clear that $H_2O_2$ from ozone, which is generated 'at the outside of the cellular reaction vessels and presenting itself directly to the redox sensors, mimics increased oxidative overflow of from cellular functional activity and triggers technically unnecessary negative feedback to the cells functional oxidative processes. At Crops Advance it was therefore concluded that:

- **Ground-level ozone generates *a false signal of metabolic perturbation***

The list of un-seen negative effects is extensive. $H_2O_2$ from ground-level ozone 'non-functionally' triggers: reduction of chlorophyll content, reduction of carboxylation capacity & activity and up-regulation of respirational activity with reduced efficiency. For electrons taking the AOX pathway, the final number of ATP generated per $O_2$ respired is 11 to 6. For electrons taking the COX pathway the final number of ATP generated per O2 respired is 29 to 6. Electrons that terminate (combine with oxygen) over the AOX pathway are only 38% efficient [51]. Mitochondria work to maintain ATP generation up to demand. In the event of AOX up-regulation mitochondria will consequently consume more carbohydrates to maintain the cell fueled. Increased carbohydrate consumption reduces dry matter production that is yield. 60 ppb ground-level ozone increase is shown to augment total dark respiration in sugarcane with 24% and in cotton with 29%, principally due to AOX up-regulation [48]. Simulation studies on grasses and rose demonstrate that a 30% increase of total dark respiration in the leaves and stems is associated with 25% to 46% yield reduction [48].

**Memory effect**: When oxidative stress and the subsequent AOX up-regulation occurs during the crops juvenile or early developmental phase, the up-regulation is set and fixed for life causing permanently reduced respirational efficiency and consequent yield reduction (!). This has been observed in a professional greenhouse production setting in the state of Minas Gerais – Brazil and for the first time brought to light by Crops Advance. The perennials rose and carnation gave up to a factor 4 variation between individual plantings in their 'four months average' yield (January – April, 2007). After 23 individual plantings of 5000 $m^2$ each were grouped by the month of their planting, the group-average productivity correlated $r^2=0.97$ with the local average ozone exposure[*] at the month of planting.

[*] Expressed as NASA´s satellite tropospheric ozone column values in Dobson Units (DU) and for the location of planting [45].

Additionally to the memory effect, over a full year cycle, leaf-chlorophyll content and accumulated dry matter inversely followed the trend of ground-level ozone. A **factor 1.6** increase of tropospheric ozone (28 to 45 DU), on average reduced leaf- chlorophyll content in rose with a **factor 1.6** (56 → 35 CCI, 2003 – 2005, n=79) and accumulated dry matter in the flower of carnation with a **factor 1.6** (2.01 → 1.26 g/flower, Feb 2007 – Feb 2008, n=54). A very sharp decline in both leaf chlorophyll content and accumulated dry matter was observed at the onset of the sugarcane burning season at the end of the August [45][48].

- **Ground-level ozone values during the juvenile phase of the crop determine the maximum attainable yield.**

## Modeling ground-level ozone increase versus change of actual yield

**An increase** of ground-level ozone is therefore expected to further reduce carbon capture *and* carbon use efficiency (CUE), both amplifying each other's effect on yield reduction.

- Crops on average are expected to have their actual yields reduced by 0.5% per ppb '1st month of planting-average' ground-level ozone increase (memory effect on CUE) [45][48].

and in addition:

- Crops on average are expected to have their actual yields further reduced by 0.5% per ppb 'crop-cycle-average' ground-level ozone increase (dynamic influence on CUE and carboxylation) [21][27][28][29][45][48].

For the individual crops, a sensitivity factor applies. In order of ozone sensitivity:

| | |
|---|---|
| cotton | 1.6 |
| soybean | 1.2 |
| ground nut | 0.6* |
| cassava | 0.6* |
| maize | 0.4 |
| sorghum | 0.4 |

*Ground nut and Cassava (estimate) are grouped with Sugar beet, Potatoes, Rape and Tobacco = 0.6. Sorghum is grouped with Millet, Corn and Rice = 0.4, Sunflower (estimate) = 1.2, Fresh vegetables in general = 1.0, Tomato = 1.4, Watermelon = 3.1, Hops 0.9 [21].

## 3. Atmospheric $CO_2$ rise - yield *change* related to general atmospheric $CO_2$ *change*

In the above it is clarified why the effect of $CO_2$ increase on actual yield cannot adequately be evaluated separately from projected ground-level ozone.

### Modeling atmospheric $CO_2$ increase versus change of actual yield

Based on Fiscus results [29], in modeling here, per crop, a combination of $CO_2$ increase relative to '$CO_2$ increase for maximum yield effect' with the projected ground-level ozone value and the crops ozone sensibility factor are combined to project the yield increasing effect of atmospheric $CO_2$ increase, for example yielding:

- for the sensibility factor = 1, for 50, 60 and 70 ppb ground-level ozone the projected yield increases are 0.074%, 0.096% and 0.117% respectively for every 1 ppm $CO_2$ increase.
- The relation between ground level ozone (in ppb // $O_{3\ ppb}$) and expected relative yield increase (as a fraction // $dY_{rel}$) per ppm $CO_2$ increase is described by the function:

$$dY_{rel} = 363^{-1} \times ([0.0078 \times O_{3\ ppb} + 0.88] - 1)$$

The $CO_2$ effect on ozone inhibition and yield improvement is assumed to be linear [27][28][29]. In our calculations we assume this to be correct for at least up to a 363 ppm atmospheric $CO_2$ increase or 730 ppm atmospheric $CO_2$. At increasing $CO_2$ levels the beneficial effect has a plateau [46]. Aubergine, a $CO_2$ sensitive crop, shows leaf yellowing at 750 ppm $CO_2$ [46]. Atmospheric $CO_2$ and ground-level ozone have opposing effects on length of crop developmental stages and total crop cycle [36][37][38]. In soybean 550 versus 372 ppm $CO_2$ delayed reproductive development and final maturation by 3 days although seed-filling was accelerated [36]. Over three growing seasons seed yield increased by 15% to 16%, principally due to ozone suppression. A 13 ppb ground-level ozone increase on the other hand shortened the growing season and reduced seed yield (seed weight and number of pods) by 15% [36]. The effect on crop cycle length on actual yield change is incorporated within the projected effects of $CO_2$ and ground-level ozone increase.

## Conclusions

The summary below outlines the “Impact of midcentury climate change on crop yield in Mozambique. Effect of rise in temperature, ground-level ozone and atmospheric CO2, a layer approach”.

| Crop | Sensitivity factor for ozone | Surface Air Temperature<br>+1.8 a 2.4 °C | | | Ground-level ozone<br>+15 a 30 ppb | | | Atmospheric $CO_2$<br>+178 ppm<br>(550 ppm) | | | Sum | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | +1.8 °C | **+2.1 °C** | +2.4 °C | +15 ppb $O_3$ | **+23 ppb $O_3$** | +30 ppb $O_3$ | +15 ppb $O_3$ | **+23 ppb $O_3$** | +30 ppb $O_3$ | Min Total | **Med total** | Max Total |
| Cotton | 1.6 | -9% | **-11%** | -13% | -24% | **-37%** | -48% | +21% | **+27%** | +33% | -12% | **-21%** | -28% |
| Soybean | 1.2 | -9% | **-11%** | -13% | -18% | **-28%** | -36% | +16% | **+20%** | +25% | -11% | **-19%** | -24% |
| Groundnut | 0.6 | -9% | **-10%** | -12% | -9% | **-14%** | -18% | +8% | **+10%** | +12% | -10% | **-14%** | -18% |
| Cassava | 0.6 | +5% | **+6%** | -+7% | -9% | **-14%** | -18% | +8% | **+10%** | +12% | +4% | **+2%** | +1% |
| Maize | 0.4 | -10% | **-13%** | -15% | -6% | **-9%** | -12% | +5% | **+7%** | +8% | -11% | **-15%** | -19% |
| Sorghum | 0.4 | -8% | **-10%** | -11% | -6% | **-9%** | -12% | +5% | **+7%** | +8% | -9% | **-12%** | -15% |

Table 3. Resume: Impact of midcentury climate change on crop yield in Mozambique. Effect of rise in temperature, ground-level ozone and atmospheric CO2, a layer approach.

Although ground-level ozone and atmospheric $CO_2$ have been given their individual column or “layer”, it has become clear that these two factors are inter-dependent when it comes to their effect on crop yield. The “feeding” or, better, the “ozone-compensating” effect of +178 ppm CO2 on yield is therefore presented per expected minimum, average and maximum ground-level ozone increase. The figures show that the projected minimum increase of +15 ppb for mid-century  ground-level ozone already annuls the effect of 178 ppm atmospheric CO2 increase on yield. This challenges any complacency:  the notion or hope that increasing CO2 levels will make good the negative effects of climate change is unfounded. . The negative effects on crop yield of ground-level ozone increase above +15 ppb together with the full negative effect of temperature increase go uncompensated by the predicted atmospheric $CO_2$ increase:  “It is the theory that decides what we can observe”.  (Einstein)

If we accept the net result of photosynthesis and respiration as the process responsible for turning our earth atmosphere aerobic and maintaining it at actual levels, perturbation of the carbon use efficiency must be expected to have the effect of reversing this dynamic balance. Although we graphically “see” a link between the anthropogenic $CO_2$ production and the atmospheric $CO_2$ increase, the causal link can be the associated anthropogenic oxidative loading of the atmosphere responsible for reducing vegetation carbon use efficiency.

In other words, atmospheric $CO_2$ increases mainly due to perturbed carbon use efficiency of global vegetation.

## Recommendations

In general it can be said that depending on a proper and timely understanding of the facts and a rational definition of priorities for actions, the cumulative loading of the atmosphere, especially with $NO_x$, NMVOC, $CH_4$ and CO as the precursors of ozone that causes oxidative stress in terrestrial vegetation including crops, can be brought under control [31].

1. For Mozambique and neighboring countries the focus should be on NOx reduction, putting a halt to *uncontrolled* hot-combustion processes, principally biomass burning.

   Concurrently, measures must be taken that help to maintain or even increase yield under the circumstances of projected climate change. This means e.g. crop selection together with measures that increase crops tolerance towards oxidative stress should have priority.

2. As total oxidative stress is the sum of the individual components responsible, including ground-level ozone, cassava is an example of how mitigation of oxidative stress from low-temperatures can result in actual yield-increase.

   Recommendation: Mitigation of oxidative stress from low-temperatures (e.g. Cassava).

3. A shift from rain-fed towards irrigated agriculture is a measure that reduces oxidative stress from drought, increasing the tolerance towards other oxidative stress components.

   Recommendation: Mitigation of oxidative stress from drought: shift from rain-fed towards irrigated agriculture (all crops).

4. As crops are specifically sensitive towards oxidative stress during their juvenile phase, mitigation of high ozone events from for example periods of large scale biomass-burning can result in significant conservation of their yield-potential.

   Recommendation: Mitigation of oxidative stress from ozone: Early planting, before the start of the burning season (All Crops).

5. A shift from rain-fed towards irrigated agriculture makes it possible to select low ozone seasons for planting that otherwise would be limited due to lack of water.
   Recommendation: Mitigation of oxidative stress from ozone: by shifting from rain-fed towards irrigated agriculture selecting a low ozone season for planting (All Crops).

6. In plant nutrition as well as in human nutrition, a joint selective group of micro-elements including but not limited to zinc, selenium and sulphur, is associated with anti-oxidant capacity. Under the circumstances of predicted climate change it becomes increasingly critical to assure adequate levels of these elements. Soil analyses should include these elements and attention should be given as to how to interpret and translate the numbers into area specific fertilizer programs.

   Recommendation: Soil analyses should include the elements associated with anti-oxidant capacity (including but not limited to Zn, Se, and S) and attention should be given as to how to interpret and translate the numbers into area specific soil corrections and fertilizer programs (All Crops).

Remark: It should also be realized that crops not only provide food in a caloric sense but are at the start of the food-chain also to assure sufficient availability of essential elements up-chain thereby preventing perturbations associated with deficiency of these elements. UNICEF states: “Zinc deficiency has been identified as a significant public health problem contributing to the deaths of about 450,000 children each year, and approximately 800,000 deaths overall. Worldwide, some 2 billion people are at risk of zinc deficiency.” [49].

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