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Economics of Adaptation to Climate Change

Annexes

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Annex 1

Cli-Crop Modeling for Agriculture

BACKGROUND

Agriculture adaptation strategies include investment in research and development (R&D) to produce crops that are more tolerant to climate changes. Climate change adaptation strategies should encourage and support crop and livestock diversification and programs that conserve water use and reduce soil erosion. The agricultural sector climate change adaptation strategies also include investment in agricultural extension services to transfer the findings of research and development—such as more drought-tolerant crop varieties and animal species—to the end users.

Successful agricultural climate change adaptation needs to consider both crops and livestock production and marketing activities from the farmers' level to the consumers' level. Climate change adaptation strategies also focus on providing storage and better marketing capabilities for cash and non-cash crop producers. Agricultural climate change adaptation strategies should target both rain-fed and irrigated lands. In irrigated areas, adaptation strategies may include programs and projects to enhance irrigation water efficiency. Adaptation strategies should also consider production and crop mix unique to each agro-ecological zone in Ghana, as well as cash crops versus food crops composition.

To be better prepared for floods or droughts, irrigation systems need to be more efficient. A higher level of irrigation efficiency plays a significant role in saving water for use in other sectors (municipal and industrial, M&I). Climate change adaptation strategies may also include providing the agricultural sector's stakeholders with modern climate forecasting capabilities. These forecasting capabilities may include modern climate monitoring stations and early warning systems. Low-income communities and households in Ghana are highly vulnerable to climate changes. Adaptation strategies work successfully in the presence of high-level coordination with the country poverty reduction programs to optimize the outcome to the poor communities.

AGRICULTURE MODELS

The agriculture models used to estimate climate change impacts in Ghana including CliCrop for modeling Ghana agricultural crops and livestock module to estimate climate change impacts on Ghana livestock.

CliCrop Model

Crop models are used to predict future yields, estimate the effects of new agricultural management techniques on yields, and understand the effects of crop and soil type on food productivity and soil fertility. Many crop models have been developed over the last thirty to forty years in response to new research and more accessible computer technology. While crop simulators continue to be primarily used for academic purposes, farmers and policy makers are beginning to trust and use them.

All crop simulators require information on soil type, crop type, and weather, because these three factors have great effects on crop production. Soil parameters can be measured in a field one point at a time, but soil properties can change drastically on a small scale both vertically and horizontally.

The growth of different crop types, which is based on complicated biological and chemical processes, also varies greatly by genotype geographic region, and even the individual plant. Weather, because of its chaotic behavior and dependence on both the large-scale and small-scale changes in the land and atmosphere, also continues to be very difficult to predict.

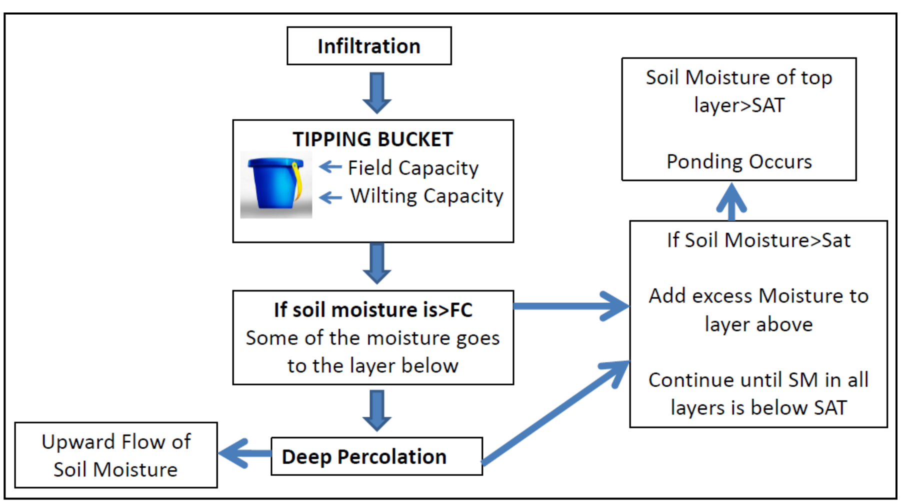
There are many existing crop models. Each model has been built to solve a specific range of problems. The model's input and calculations depend on the input available and the accuracy that is required. For example, CropWat, a model developed by the Food and Agriculture Organization of the United Nations, is a very simple 1-dimensional crop model. CropWat requires very limited input, assumes no vertical differences in soil moisture, and assumes that the soil moisture cannot exceed field capacity. CropWat also simulates water stress on crops, ignoring any nutrient or solar stresses on a daily time-step. But CropWat is a tool to plan irrigation patterns for use by poor farmers in arid to semi-arid regions. So, CropWat does not need to calculate the effects of waterlogging or daily precipitation patterns. The model can assume that the farmer will irrigate and will not overirrigate. SWAP (soil-water-atmosphere-plant), on the other hand, is a much more complicated soil moisture scheme, implementing Richard's equation on a time-step of less than 30 minutes. SWAP requires more input and a faster computer, but models the movement of moisture in the soil layer using a more dynamic approach, allowing SWAT to claim more confidence in its solution.

CliCrop was developed because there were no existing models that were adequate to solve the problems specific to climate change cha. Specifically, these problems include modeling two water management techniques, zai holes and mulching, and also estimating the effects of climate change on crop yields, including both water stress from insufficient and excess water (Fant 2008).

Structure of CliCrop

The effects of the atmosphere are modeled indirectly in the soil layer through the extraction of ET and the infiltration into the soil layers. The model uses the soil properties and precipitation amount to calculate the infiltration using the USDA Curve Number method. Then the model calculates the soil moisture in each soil layer. The model then calculates the amount of moisture allowed to percolate into the deep soil layers. The water table is then measured and a yield is calculated – Figure A-1

Figure A-1 ClipCrop Structure



Inputs

CliCrop was designed for large-scale yield calculations, using both future and historical weather data and available soil data. Input into CliCrop is simple and the amount of required input is minimized in order to avoid as much error as possible involved with the input.

Precipitation

Since CliCrop runs on a daily timescale, total daily precipitation data is required in millimeters per day. The historic precipitation data that is currently built into the model comes from the Collaborative Historical African Rainfall Model (CHARM). The CHARM database contains 36 years (1961–96) of daily historic rainfall for all of Africa estimated by satellite and rain gauge data (Funk et al. 2003).

Potential Evapotranspiration (ET)

Potential Evapotranspiration is a measurement of the atmosphere's ability to extract moisture from the soil both through evaporation and transpiration measured in mm/day. Table A-1 below shows the range of potential ET for different climatic regions (Allen, et al. 1998)

Table A-1 Range of Potential ET

Regions	Mean daily temperature (°C) Cool ~10°C	Moderate 20°C	Warm >30°C
Tropics & subtropics			
humid & sub-humid	2 - 3	3 - 5	5 – 7
arid & semi-arid	2 - 4	4 - 6	6 - 8
Temperate Region			
-humid & sub-humid	1 - 2	2 - 4	4 – 7
-arid & semi-arid	1 - 3	4 - 7	6 - 9

Potential evapotranspiration is estimated based on a mean daily temperature, daily temperature range, and latitude. The modified hargreaves equation (Hargreaves and Allen 2003) is used to find the potential ET based on these parameters.

Crop Type

All of the crop parameters used by CliCrop were first developed by FAO in CROPWAT (Allen et al. 1998). CliCrop retrieves the crop parameters based on the crop specified by the user. These parameters include:

Single (time averaged) crop coefficients, Kc: These values are used in the calculation of actual and potential evapotranspiration. There are three coefficients for each crop. These values are used to create a coefficient for each day of the growing season (see Table 12 in FAO Drainage Paper No. 56; Allen et al. 1998).

Basal Crop Coefficient, Kcb: These values are only used to find the reduction in potential evapotranspiration caused by mulching. There are three coefficients for each crop similarly to Kc. These values can be used to calculate actual and potential transpiration (see Table 17 in FAO Drainage Paper No. 56; Allen et al. 1998).

Crop Stage Durations: The length in days of each of the four stages in the growing season. These stages include the initial, development, middle, and final.

Yield Coefficients: Values used to weight the effect of water losses on the yield for each of the four stages of growth. These values are used in the yield calculation equation.

Root Growth Per Day: Roots will grow at this length (in mm) per day when growth is allowed.

Initial Root Depth: It is assumed that the root zone starts at an initial depth. This concept and value are both borrowed from CROPWAT and Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

Growing Season Duration: Length of growing season in days. This value is the sum of the crop stage durations explained above.

Soil Properties

Estimations if Unknown is selected: The only soil properties required for CliCrop to run are hydraulic conductivity, wilting point, field capacity, and saturation. These parameters are estimated based on the location. A data set was acquired from the FAO Soil Map of the World that contains clay and sand content. The wilting point and field capacity are estimated based on methods developed by the National Center for Atmospheric Research (NCAR) (Oleson, et al. 2004). A semi-impervious layer is assumed to be at a depth of 2 meters from the soil surface. The semi-impervious layer allows soil moisture to percolate at a rate of 1 percent of the hydraulic conductivity when excess soil moisture exists in the bottom layer.

When either the Wise Soil Profile is used or the soil parameters are known, the model assumes a semi-impervious layer at the bottom on the soil profile, as described above. When the soil parameters are known, the model also assumes a semi-impervious layer at 2 meters.

Water Transport

The Cli-Crop model solves for soil moisture in each soil layer. By default, the model has 20 layers, each 10 cm deep. If the WISE soil profile is used, the number of layers is determined by the number of layers in the WISE soil profile (Fant 2008).

Once infiltration is calculated, the total amount of moisture infiltrated into the soil layer is added to the first layer. That layer is filled from wilting point to field capacity. Most of the moisture over field capacity is allowed to percolate to the layer below. The model then checks if the soil moisture in the layer is above saturation. If so, the model adds the moisture above saturation to the layer above until all moisture has found "space." If the top layer is saturated and excess soil moisture remains, the excess is considered lost to ponding. The model does this for each layer from the top to the bottom soil layer. At the bottom soil layer the model calculates deep percolation, which allows some of the moisture in the bottom soil layer to percolate past the semi-impervious layer. This moisture is considered lost to the deep soil layers. The model then checks one more time for any layer whose soil moisture is above saturation. Once all of this is finished, the model calculates the upward flow of soil moisture.

Effective Precipitation

Once the model retrieves the precipitation, the runoff is calculated based on the hydraulic conductivity of the first soil layer, the moisture content of the first soil layer, and the cover type using the National Resource Conservation Service's (NRCS) curve number method. The curve number is estimated by a graph created by NRCS and printed in the Drainage Manual produced by the Bureau of Reclamation, a part of the U. S. Department of the Interior (see graph in the appendix) (Bureau of Reclamation 1993).

Evapotranspiration (ET)

The effective precipitation is then added to the moisture of the fist layer of the soil profile. CliCrop then calculates the soil moisture, one layer at a time, starting with the top layer and moving down to the bottom of the soil profile. During the dormant season, evaporation is removed from the top 12.5 cm of the soil profile using the following equations from FAO Irrigation and Drainage paper No. 56 (Allen et al. 1998):

Equation 1

$$TEW^{l} = (FC^{l} - 0.5 \cdot WP^{l}) \cdot delZ$$

$$K_r^{l,t} = \frac{SM^{l,t-1} - 0.5 \cdot (WP^{l} \cdot delZ)}{(1 - pe) \cdot TEW^{l}}$$

$$ETS^{l,t} = \frac{(ET0^{t} \cdot asm)}{nls0}$$

$$ETSA^{l,t} = ETS^{l,t} \cdot K_r^{l,t}$$

$ETC^{l,t}$ = crop specific ET demand (mm)
$ET0^{t}$ = potential ET at day t (mm)
K_C^{t} = crop coefficient at day t
$nlsr^{d}$ = number of layers in root zone
p = soil water depletion fraction
p_{tab} = soil water depletion fraction for no stress listed in table 22 of FAO Irrigation and Drainage Paper No. 56
TAW^{l} = total available water of layer l (mm)
delZ = thickness of layer l (mm)
FC^{l} = field capacity of layer l
WP^{l} = wilting point of layer l
$K_s^{l,t}$ = limiting coefficient for the calculation of actual ET for layer l at day t, $0 \le K_r^{l,t} \le 1$
$SM^{l,t-1}$ = soil moisture of layer l at the day before t (mm)
$ETA^{l,t}$ = soil moisture removed from layer l at time t due to ET (mm)

CliCrop contains two methods for determining ET: the single crop coefficient method and the dual crop coefficient method. If the single crop coefficient method is used during the growing season, ET is removed from the root zone using the following equations from FAO Irrigation and Drainage paper No. 56 (Allen et al. 1998):

Equation 2

$$ETC^{l,t} = \frac{ET0^{t} \cdot K_C^{t}}{nlsr^{d}}$$

$$p = p_{tab} + 0.04 \cdot (5 - ETC^{l,t})$$

$$TAW^{l} = delZ \cdot (FC^{l} - WP^{l})$$

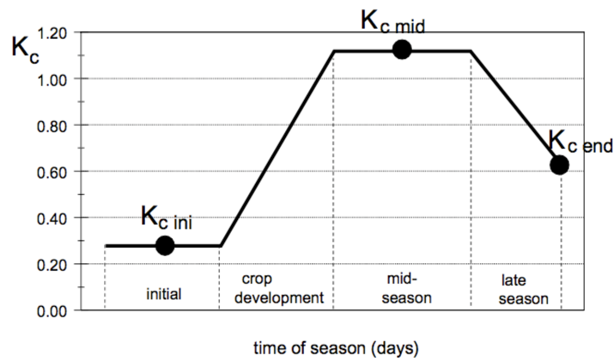
$$K_s^{l,t} = \frac{SM^{l,t-1} - WP^{l} \cdot delZ}{(1 - p) \cdot TAW^{l}}$$

$$ETA = K_s^{l,t} \cdot ETC^{l,t}$$

$ETC^{l,t}$ = crop specific ET demand (mm)
$ET0^{t}$ = potential ET at day t (mm)
K_C^{t} = crop coefficient at day t
$nlsr^{d}$ = number of layers in root zone
p = soil water depletion fraction
p_{tab} = soil water depletion fraction for no stress
(Listed in table 22 of FAO Irrigation and Drainage Paper No. 56)
TAW^{l} = total available water of layer l (mm)
delZ = thickness of layer l (mm)
FC^{l} = field capacity of layer l
WP^{l} = wilting point of layer l
$K_s^{l,t}$ = limiting coefficient for the calculation of actual ET for layer l at day t, $0 \le K_r^{l,t} \le 1$
$SM^{l,t-1}$ = soil moisture of layer l at the day before t (mm)
$ETA^{l,t}$ = soil moisture removed from layer l at time t due to ET (mm)

Figure A-2 below shows a typical change in the crop coefficient, and therefore crop ET demand for the four development stages.

Figure A-2 Evolution of Crop Coefficient during the Growing Season



If the dual crop coefficient method is used, transpiration and evaporation are calculated separately during the growing season. In order to apply the changes made to transpiration caused by CO_2 fertilization. In general, this method was also taken from FAO Irrigation and Drainage paper No. 56 (FAO 56) (Allen et al. 1998). In this method a different crop coefficient was used: the basal crop coefficient (K_{cb}).

First, using a ratio of the precipitation and PET of the growing season, a climate classification method was used to find the minimum relative humidity (RH_{min}) for the growing season (Cazalac, PHI/UNESCO n.d.). Next, the crop height (h) is estimated based on the max crop height given in FAO 56 multiplied by a ratio of the crop specific demand of that day and the maximum crop specific demand. The crop height does not decrease, it only increases. Then K_{Cmax} (represents an upper limit on the evaporation or transpiration from any cropped surface) is calculated based on equation 72 in FAO 56, and shown below:

Equation 3 $$K_{C\max} = \max(\{1.2 + [0.04(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\},\{K_{cb} + 0.05\})$$

K_{Cmax} is then used to calculate the fraction of the ground covered by vegetation (f_c) using the eqution below (equation 76 in FAO 56).

Equation 4 $$f_c = \left(\frac{K_{cb} - K_{c\min}}{K_{c\max} - K_{c\min}}\right)^{(1+0.5h)}$$

Where K_{cmin} is minimum K_c for dry bare soil, estimated to be 0.175 based on FAO 56. The fraction of soil surface that is moist, and therefore exhibits moist soil evaporation (f_{ew}) is calculated using the following equation (equation 75 from FAO 56).

Equation 5 $$f_{ew} = \min(1 - f_C, f_W)$$

Where f_W is taken from Table 20 in FAO 56, based on the type of irrigation, if any, that is used. Then a dimensionless evaporation reduction coefficient, K_r, is calculated using equation 74 in FAO 56 shown below.

Equation 6 $$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \text{ for } D_{e,i-1} > REW$$

Where TEW is the total evaporable water (FC – 0.5*WP), REW is the readily available water and is calculated using table 19 in FAO 56. $D_{e,i\text{-}1}$ is the cumulative depth of evaporation, calculated from the previous day. The soil evaporation coefficient, K_e, is calculated using equation 71 in FAO 56 shown below.

Equation 7 $$K_e = K_r (K_{C\max} - K_{cb})$$

The ET demand (ETC) is then calculated as

Equation 8 $$ETC = \frac{(K_{cb} + K_e) ET_0}{nlsr}$$

And the actual ET removed from the soil layers is calculated the same as the single crop coefficient method, only using the above equation for ETC.

Soil Layer Percolation

Once ET is removed from the soil layer, percolation from the layer above is added based on the soil water excess equation borrowed from SWAT (Neitsch, Arnold et al. 2005).

Equation 9 $$TT = \left(\frac{SAT^l - FC^l}{HC^l} \right) \cdot delZ$$

$$SW_{excess}^{l,t} = SM^{l,t} - FC^l$$

$$Perc^{l,t} = SW_{excess}^{l,t} \cdot \left[1 - \exp\left(\frac{-\Delta t}{TT} \right) \right]$$

TT = travel time (hr)
SAT^l = moisture content at saturation of layer l
FC^l = moisture content at field capacity
HC^l = hydrualic conductivity (mm/hr)
delZ = thickness of layer (mm)
$SW_{excess}^{l,t}$ = soil water excess, $SW_{excess}^{l,t} \geq 0$ (mm)
$SM^{l,t}$ = soil moisture of layer l (mm)
$Perc^{l,t}$ = moisture to percolate to layer below (mm)
Δt = length of one time step (hrs)
Soil moisture is moved to the layer below only if the soil layer exceeds field capacity.

Soil moisture is moved to the layer below only if the soil layer exceeds field capacity.

Ponding

After ET and percolation are removed, if the layer's soil moisture exceeds saturation, any soil moisture above saturation is added to the layer above until either, all of the soil moisture has been placed, or ponding occurs at the soil surface. Any ponding is considered lost.

Deep Percolation

If percolation, as described above, continues to the bottom layer of the soil profile, deep percolation occurs. The most that is allowed to percolate out of the soil profile is 1 percent of the hydraulic conductivity per day. The rest is added to the layer above until either all layers have reached saturation (in which case ponding occurs), or until all moisture has been placed.

Soil Water Upward Flow

The following equations are used to estimate the movement of soil moisture against gravity. The method was borrowed from the DSSAT model.

Equation 10

$$THET1 = SW(L) - LL(L)$$
$$THET2 = SW(L+1) - LL(L+1)$$
$$DBAR = (0.88cm^2 day^{-1}) \times \exp(35.4 \times (THET1 \times 0.5 + THET2 \times 0.5)$$
$$FLOW = DBAR \times (THET2 - THET1)/((DLAYR(L) + DLAYR(L+1)) \times 0.5)$$

THET1 = volumetric water content of layer L, changes daily (cm)
THET2 = volumetric water content of layer L+1, changes daily (cm)
SW = soil moisture, changes daily (cm)
LL = soil layers lower limit (cm)
DBAR = assumed average diffusivity (cm day^{-1})
FLOW = soil moisture moved from layer, L + 1, to layer, L

Water Table

The water table is used to determine losses due to waterlogging. The height of the water table is measured from the bottom soil layer to the furthest saturated layer. If no layers are saturated, the height of the water table is considered to be zero. If the first layer is saturated, the height of the water table is equal to the depth of the soil profile. So, the height of the water table is not necessarily the height to which the soil is saturated. The water table height is independent of the moisture of all soil layers except the saturated layer closest to the surface.

Yield Reductions / Improvements and Adjustments to Crop Behavior Due to Climate

Yield calculations are based primarily on the ratio of actual ET and potential ET. Five yield values are calculated; one for each of the four development stages, and one for the whole season. The least of the five, considered the limiting yield, is reported as the true yield. Each yield value is calculated by the equation below, which was borrowed from the FAO 56 (Allen et al. 1998).

Equation 11

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y^d\cdot\left(1-\frac{ETC^d}{ETA^d}\right)$$

$$\%Yield^d=\frac{Y_a}{Y_m}$$

Y_a = predicted actual yield
Y_m = maximum yield
K_y^d = yield coefficient, different for development stage d
ETC^d = sum of daily ET crop demand for development stage d
ETA^d = sum of daily actual ET for development stage d
$\%Yield^d$ = ratio of actual yield over maximum yield, value reported by CliCrop

Waterlogging

The reduction in yield due to waterlogging is simulated in CliCrop with two functions; an oxygen loss reduction coefficient, SEW_{30}, and the root growth hindrance.

SEW_{30}

SEW_{30} was proposed by Sieben in 1964, and is a method to calculate waterlogging losses based on experimental data. SEW_{30} is a measurement of the magnitude and duration of the root zone's saturation.

Equation 12

$$SEW_{30}=\sum_{t=1}^{DUR}(30-x^t)$$

$$RY=\begin{cases}0.91-0.00031\cdot SEW_{30} & SEW_{30}>200\\ 1-0.00076\cdot SEW_{30} & \mathrm{SEW}_{30}\le 200\end{cases}$$

$$Yield=Yield_{wwl}-(1-RY)$$

SEW_{30} = sum of excess water, only calculated when the height of the water table is within 30 cm of the soil surface
t = day of growing season
DUR = duration of growing season
x^t = distance from soil surface to water table at day t
RY = reduced yield due to waterlogging
Yield = yield of season
$Yeild_{wwl}$ = yield without waterlogging losses
(Mohanty, et al. 1995)

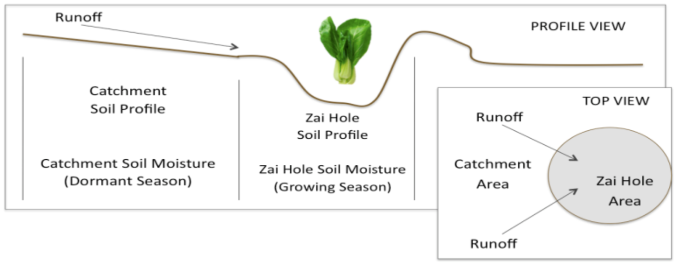
Root Growth

When the watertable height is measured to be within the root zone, the roots are not allowed to grow for that day. This growth hindrance could cause yield reduction due to water losses for the crop in the future, since the roots may not be deep enough to access soil moisture in the deeper soil layers.

Zai Holes

Since there are no preceding models that have estimated the effect of zais on crop yields, and therefore no modeling process has been established or tried, the following is an attempt to simulate the process dynamically. The process was formed by the imagination of the creators of CliCrop. The effects of the zai holes are simulated with two separate soil profiles, a catchment soil profile and a zai-hole soil profile. Both soil profiles have the same soil parameters; the only difference is the amount of effective precipitation that infiltrates into the profile. At the end of the growing season, the moisture in the soil profile is assumed to be an average of the two profiles for dormant season calculations. Figure A-3 shows a diagram of the zai hole modeling process.

Figure A- 3 Diagram of the Zai Hole Modeling Process



Catchment Soil Profile

The catchment soil profile is treated very similarly to the profile in the dormant season. Evaporation is removed (based on FAO 56) and the soil moisture transport between layers is calculated using the SWAT method. A water table height is not calculated because it is never used.

Zai Hole Soil Profile

The runoff from the catchment area is assumed to drain into the zai hole based on the catchment efficiency (determined by user). If the catchment efficiency is 100 percent, all of the runoff from the catchment enters the zai hole soil profile. If the catchment is 0 percent, only 50 percent of the runoff enters the zai hole soil profile and the other 50 percent is assumed lost. For any value in between 0 percent and 50 percent catchment efficiency, the runoff caught by the zai hole is calculated using a linear relationship.

Equation 13

$$\text{Runoff Caught} = \left(\frac{\text{Catchment Efficiency}}{2} + 50\right) \cdot \mathit{Runoff} \cdot \text{Zai Ratio}$$

Runoff refers to the runoff from the catchment soil profile, and zai ratio is the zai area over the total area.

Mulching

None of the crop models that were studied prior to the construction of CliCrop included a process for modeling the effects of mulch on crop yields. But some research has been done on this topic and is used here. The effects of mulching are simulated in three separate ways: reduction in evapotranspiration, runoff reduction, and the organic matter increase.

Reduction in Evapotranspiration

Organic mulch has been proven to reduce the temperature at the soil surface, thus decreasing evapotranspiration. FAO 56 proposed a simple method to mathematically simulate this reduction by reducing the crop coefficients based on the amount of ground that is covered by mulch.

Equation 14

$$K_{C1}^{t}{}' = K_{C1}^{t} \cdot (1 - mulch/2)$$

$$K_{C2}^{t}{}' = K_{C2}^{t} - mulch/2 \cdot (K_{C2}^{t} - K_{Cb2}^{t})$$

$$K_{C3}^{t}{}' = K_{C3}^{t} - mulch/2 \cdot (K_{C3}^{t} - K_{Cb3}^{t})$$

$K_{C1}^{t}{}'$ = crop coefficient for the initial stage after reduction due to mulching
K_{C1}^{t} = crop coefficient for the initial stage before reduction due to mulching
mulch = percent of ground covered by organic mulch
$K_{C2}^{t}{}'$ = crop coefficient for the middle stage after reduction due to mulching
K_{C2}^{t} = crop coefficient for the middle stage before reduction due to mulching
K_{Cb2}^{t} = basal crop coefficient for the middle stage
$K_{C3}^{t}{}'$ = crop coefficient for the late stage after reduction due to mulching
K_{C3}^{t} = crop coefficient for the late stage before reduction due to mulching
K_{Cb3}^{t} = basal crop coefficient for the late stage

So, for every 10 percent of the ground that is covered by mulch, the crop coefficient is reduced by 5 percent. The crop coefficient for the initial stage is reduced much more than the second and third stages because the difference between the basal crop coefficient and the original one is usually fairly small. So, most of the benefit from ground cooling occurs at the beginning of the season (Allen et al. 1998).

Runoff Reduction

Runoff is reduced by organic mulch because the mulch causes more friction and an increase in the travel path. Due to a lack of available research on this phenomenon, a very simple method was chosen. When mulch is used, the curve number is reduced based on the following equation:

Equation 15 $$CN' = CN - mulch \cdot 30$$

CN' = reduced curve number due to organic mulching
CN = curve number before mulch reduction
mulch = % of ground covered by mulch

Adjustments to Crop Coefficients Due to Climate Changes

Whether the single-crop coefficient method (K_c) or the dual-crop coefficient method (K_{cb}) is used, the crop coefficients change due to changes in climate. This means that the crop's demand for water responds to changes in precipitation and Potential ET. FAO 56 suggests a method for adjusting these crop coefficients based on these weather changes. The CliCrop code adjusts these coefficients using the method presented by FAO 56 (Allen et al. 1998).

During the initial stage, the majority of ET is evaporation, while during the other three stages the majority of ET is generally transpiration. So the initial crop coefficient is calculated differently depending on whether the single- or the dual-crop coefficient method is used. If the single-crop coefficient method is used, the crop coefficient for the initial stage ($K_{C\ init}$) is calculated using the following equation.

Equation 16

$$\mathrm{t_W} = \frac{L_{ini}}{n_W + 0.5}$$

$$E_{SO} = ET_0 \cdot 1.15$$

$$t_1 = REW / E_{SO}$$

$$K_{C\,\mathrm{ini}} = \frac{TEW - (TEW - REW)\exp\left(\frac{-(t_W - t_1 \cdot E_{SO}\left(1 + \frac{REW}{TEW - REW}\right))}{TEW}\right)}{t_W \cdot ET_0}$$

Where L_{ini} is the length of the initial stage; n_w is the number of wetting events in the initial stage; ET_0 is the average potential ET in the initial stage; REW is the readily available water estimated using the average wilting point of the soil, the average field capacity of the soil, and Table 19 from FAO 56; and TEW is the total evaporable water (FC – 0.5*WP). For the other two crop coefficients, $K_{c\ mid}$ and $K_{c\ end}$, the following equation is used.

Equation 17 $$K_c = K_c + 0.004(RH_{\min} - 45)\left(\frac{h}{3}\right)^{0.3}$$

Where the minimum relative humidity (RH_{min}) is calculated over the development stage, and mid-season stage, for $K_{c\ mid}$ and $K_{c\ end}$, respectively.

If the dual-crop coefficient method is used, the basal crop coefficients are estimated by the following equation.

Equation 18 $$K_{cb} = K_{cb} + 0.004(RH_{\min} - 45)\left(\frac{h}{3}\right)^{0.3}$$

Where the minimum relative humidity (RH_{min}) is calculated over the initial stage, development stage, and mid-season stage, for $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$, respectively.

Adjustments to Crop Stage Lengths Due to Climate Change

The crop stage lengths also respond to changes in climate. As the temperature increases, the stage lengths shorten. The following equation was used to change all four of the crop stage lengths (Wahaj et al. 2007).

Equation 19 $$\Delta D_0 = \frac{D_0 \cdot \Delta T}{(T_{Ave} - T_{base})}$$

Where ΔD_0 is the change in the stage length (days) rounded to the nearest integer; D_0 is the original length of the crop stage, supplied as input; ΔT is the average change in temperature from the base temperature and the year of simulation during the given crop stage; T_{Ave} is the average temperature of the given crop stage; and T_{base} is a crop-specific parameter, supplied as input.

CO_2 Fertilization

Studies have shown that with increased CO_2 crop transpiration decreases due to increased stomatal resistance. In one such study, ratios are provided for C3 and C4 crops. CliCrop uses these ratios to reduce the transpiration demand as CO_2 increases using the following equations (Rosenzweig and Iglesias 1998).

Equation 20 $$CO_{2\,\mathrm{fert}} = \left[\left(\frac{SR-1}{555-330}\right)(CO_2 - 330) + 1\right]$$

$$T_{cb} = T_{cb} / CO_{2\,\mathrm{fert}}$$

Where SR is the stomatal resistance coefficient (for C3 crops SR = 49.7/34.4, and for C4 crops SR = 87.4/55.8); CO_2 is the amount of CO_2 in the atmosphere in parts per million; and T_{cb} is the crop transpiration demand.

The Livestock Model

Although the direct effects of heat stress and changes in precipitation on livestock have not been studied extensively, warming is expected to alter the feed intake, mortality, growth, reproduction, maintenance, and production of animals. In addition, changing climate conditions are expected to affect the availability of feed for livestock. Collectively, these effects are expected to have a negative impact on livestock productivity (Thornton et al. 2009).

SM use this model to evaluate fixed changes in temperature of 2.5°C and 5.0°C, and in precipitation of +/-15 percent from the baseline. The resulting predicted changes in the probability of selecting an animal, expected income per animal, and the total number of animals under these changing climate conditions are presented in Table A-2.

Note in all three tables that beef cattle and chickens are more sensitive to changes in climate than dairy cattle, goats, and sheep. In prior studies, beef cattle have been found to experience increases in mortality, reduced reproduction and feed intake, and other negative effects as temperatures rise (Adams et al. 1999). Chickens are particularly vulnerable to climate change because they can only tolerate narrow ranges of temperatures beyond which reproduction and growth are negatively affected. Further, increases in temperature caused by climate change can be exacerbated within enclosed poultry housing systems. Depending on the animal type, both decreases and increases in precipitation could have a positive or negative effect on livestock.

Table A-2 Predicted Change in the Probability of Selecting Each Animal as the Primary Animal Type for the Farm

	Beef cattle	Dairy cattle	Goats	Sheep	Chickens
Baseline probability	11.8%	23.1%	23.4%	19.4%	22.3%
Increase temp 2.5C	-1.7%	+0.4%	+0.8%	+3.3%	-2.8%
Increase temp 5C	-3.8%	+2.1%	0.0%	+8.7%	-7.0%
Decrease rain 15%	-0.3%	+1.8%	-1.2%	1.1%	-1.4%
Increase rain 15%	-0.1%	-1.5%	1.5%	-1.1%	+1.0%

Predicted Change in Net Income per Animal

	Beef cattle	Dairy cattle	Goats	Sheep	Chickens
Baseline income	145.54	132.09	6.49	11.77	1.14
Increase temp 2.5C	-27.80	-3.40	-0.81	-2.55	-0.34
Increase temp 5C	-47.09	-21.36	-0.54	-3.49	-0.55
Decrease rain 15%	13.91	-0.42	-0.06	1.03	0.03
Increase rain 15%	-7.08	3.78	0.29	-0.58	-0.02

Predicted Change in Number of Animals per Farm

	Beef cattle	Dairy cattle	Goats	Sheep	Chickens
Baseline number	63.47	23.84	15.36	34.05	790.09
Increase temp 2.5C	-9.00	1.84	1.45	0.35	-112.61
Increase temp 5C	-18.96	2.88	2.14	3.20	-183.84
Decrease rain 15%	7.52	0.13	-0.90	2.99	50.30
Increase rain 15%	-6.33	-0.11	0.99	-1.80	-45.20

Table A-3 combines the above effects into predicted changes in expected farm-level income. SM predict a reduction in expected income of 32 percent and 69 percent resulting from a 2.5°C and 5°C increase in mean temperatures. A 15 percent decrease in rain causes a 2.5 percent increase in expected income, whereas a 15 percent increase causes a reduction of 1.9 percent. Regarding this counterintuitive finding on increases in precipitation, SM cite Sankaran et al. (2005), who explain that increases in rainfall may cause changes in land cover from savannah to forests that will reduce grazing opportunities for livestock. Finally, SM produces a 95 percent confidence interval on each of their estimated climate change effects, as shown in the table below.

Table A-3 Predicted Change in Expected Income

	Mean (US$/farm)	% Change	Bootstrap lower 95%	Bootstrap upper 95%
Expected income	3,023			
Increase temp 2.5C	-964	-31.90%	-1,077	-722
Increase temp 5C	-2,083	-68.89%	-2,452	-1,631
Decrease rain 15%	184	2.49%	139	207
Increase rain 15%	-108	-1.88%	-111	-60

Transfer Approach and Assumptions

The goal of the current analysis is to generate vectors of projected changes in expected income from livestock within each AEZ. To do so, the analysis uses the framework and findings of SM coupled with country-specific livestock data and climate projections. The transfer involves the following steps

Step 1: Develop baseline livestock choice probabilities within each AEZ

It was assumed that the baseline probability of choosing livestock as a farm's primary animal is revealed through the existing distribution of livestock types, measured in tropical livestock units (TLU) in each AEZ (where AEZ1-coastal, AEZ2-forest, AEZ3 - south savannah, AEZ4 -north savannah).

In order to generate the percentages of each livestock type at the AEZ level, data were first gathered on livestock counts in Ghana from FAOSTAT and FAO's CountrySTAT. FAOSTAT provides the breakdown of total cattle, goats, sheep, and chickens for Ghana in 2000, but does not provide a breakdown by region. FAO's CountrySTAT provides data on the distribution of cattle, goats, and sheep slaughtered across the 10 administrative regions of Ghana in 2008, which were used as a distribution for the live animal counts from FAOSTAT (i.e., after applying the distribution, the year 2000 total animal count is maintained).[1] CountrySTAT also provides the live chicken counts by region for 2009; this distribution is applied to the year 2000 chicken counts from FAOSTAT. These data at the regional level were then distributed spatially to the AEZ level.

Different livestock types are brought onto a comparable scale (i.e., to be able to compare cattle and chickens) using the tropical livestock unit (TLU) conversions from FAO (specifically, from Otte and Chilonda 2002). On this scale, a TLU of 1.0 is an animal weighing 250 kg; cattle are 0.7 TLU, sheep and goats each are 0.1 TLU, and chickens are 0.01 TLU. The overall numbers of livestock from the above steps are converted to TLUs. These values are presented in Table A-4 below, and are taken to be the baseline probabilities of choosing each livestock type in each Ghanaian AEZ.[2]

Table A-4 Distribution of TLUs by Livestock Type Across AEZ in Ghana

AEZ	Beef Cattle	Cows	Goats	Sheep	Chickens
1	7.6%	2.3%	44.6%	39.1%	6.5%
2	43.8%	13.2%	17.4%	15.2%	10.4%
3	33.0%	10.0%	16.9%	14.7%	25.5%
4	33.0%	10.0%	25.5%	25.7%	5.9%
Total	38.2%	11.5%	19.8%	17.6%	12.9%

Step 2: Convert SM's absolute differences from baseline to percentage deviations

As seen in Table A-4 above, SM estimate absolute differences from the baseline probabilities in response to changes in temperature and precipitation. Because the baseline in this analysis differs from theirs in each AEZ, SM's absolute changes are converted to percentage deviations (see Table A-5). These percentages are then multiplied by the baseline probabilities in each AEZ to generate the changes in animal choice probability resulting from changes in temperature and precipitation

[1] Implicit in this approach is the assumption that the distribution of slaughtered animals reflects the underlying distribution of live animals.

[2] An alternative adjustment approach considered was to divide the total number of each animal type in Ethiopia by SM's estimated baseline livestock per farm (Table A-1-3). This generates the number of farms by primary livestock type, which could be used to generate a distribution of farms by livestock type and substitute for Table A-4. This approach, however, assumes that farms only have one type of livestock, and therefore may significantly overweigh animals that are often kept as a non-primary livestock type.

Table A-5 Deviations from Baseline Probabilities in Response to Changes in Climate

	Beef cattle	Dairy cattle	Goats	Sheep	Chickens
Increase temp 2.5C	-14.4%	+3.4%	+6.8%	+28.0%	-23.7%
Increase temp 5C	-32.2%	+17.8%	0.0%	+73.7%	-59.3%
Decrease rain 15%	-2.5%	+15.3%	-10.2%	+9.3%	-11.9%
Increase rain 15%	-0.8%	-12.7%	+12.7%	-9.3%	+8.5%

Step 3: Develop adjustment factors to scale between calculated results and SM's findings

Using the methods that SM outline for developing the expected income per farm, this analysis attempted to reproduce SM expected incomes based on the original SM selection probabilities, income per animal, and number of animals per farm (i.e., the sum product of these across livestock types). These calculated values are in the third column of Table A-6, and differ from SM's results presented above (and again in the second column of Annex Table A-6). To ensure that the results of this analysis are scaled appropriately to SM's, an adjustment factor is applied to the expected income and each of the changes in expected income. This adjustment factor (fourth column of Table A-6) is applied to each of the country-specific calculations at the AEZ level.

Table A-6 Adjustment Factors for Differences in Reported and Calculated SM Results

	Predicted Change in Expected Income (US$/farm)		Adjustment Factor
	Reported by SM	Calculated from SM Methods and Results	
Expected income	3,023	2,119	1.43
Increase temp 2.5°C	-964	-494	1.95
Increase temp 5°C	-2,083	-857	2.43
Decrease rain 15%	184	292	0.63
Increase rain 15%	-108	-209	0.52

Step 4: Estimate predicted changes in livestock income in response to incremental changes in temperature and precipitation

Next, the changes in expected livestock income in each Ghana AEZ are generated corresponding to 1°C increases in temperature and 1 percent changes in precipitation. First, the baseline expected incomes in each AEZ are estimated, which follows the SM approach outlined above, except that the values are multiplied by the expected income adjustment factor:

Equation 21

$$M^{AEZ} = c^M \sum_l p_l^{AEZ} m_l n_l$$

Where :

M^{AEZ} = Expected income in each AEZ

c^M = Constant adjustment factor to SM results for baseline income

p_l^{AEZ} = Probability of choosing each livestock type in each AEZ

m_l = Income per animal

n_l = Number of each livestock type per farm

These baseline expected income levels are then used to generate changes in expected income under the four climate changes analyzed by SM based on changes in probability of livestock choice, expected income per animal, and number of animals. These changes for each AEZ and climate change type are shown in the equation below. Note that the second term is the baseline expected incomes prior to adjustment, and that the change relative to that baseline is then multiplied by the appropriate multiplier.

Equation 22

$$\Delta M^{cAEZ} = c^c \sum_l [p_l^{AEZ}(1+\delta_l^{cp})(m_l + \delta_l^{cm})(n_l + \delta_l^{cn}) - p_l^{AEZ} m_l n_l]$$

Where :

ΔM^{cAEZ} = Change in expected income in each AEZ and level of increased temperature c

c^c = Constant adjustment factor to SM results for each of the two levels of increases in temperature c (i.e., + 2.5°C, + 5°C)

δ_l^{cp} = Percentage change in the probability of choosing each livestock type given a change in temperature c

δ_l^{cm} = Change in income per animal given a change in temperature c

δ_l^{cn} = Change in number of each livestock type per farm given a change in temperature c

Annex Table A-18 provides the results of this procedure both in terms of the mean expected change in income and the percent change from baseline levels. The key numbers in the table are shaded in gray; these are percent changes in expected income resulting from incremental changes in climate, and are applied directly to the development of the response of livestock to climate between 2001 and 2050. There are three important observations of note in this table:

- The expected incomes vary widely relative to those estimated by SM – from \$1,500 to \$6,600 here versus \$3,000 in SM. This is because some AEZ's have higher probabilities of choosing more profitable animals such as beef cattle over goats, whereas in others less profitable animals have a higher likelihood of being selected (see Annex Table A-15 above).
- Temperature increases to 5°C result in losses that exceed 100 percent of baseline incomes in two of the AEZs. Although it is feasible for net incomes to be negative if revenues fall below fixed costs, income losses are capped in the analysis of climate effects (described below) at 100 percent, but the analysis relies on the incremental impacts between 2.5°C and 5°C presented in Table A-7.

Table A-7 Mean Expected Changes in Income Resulting from Changes in Temperature and Precipitation, and Percent Changes from Baseline

	Mean (US\$/farm)				Percent Change from Baseline			
	AEZ 1	AEZ 2	AEZ 3	AEZ 4	AEZ 1	AEZ 2	AEZ 3	AEZ 4
Expected Income	1,470	6,605	5,235	5,055				
Increase temp 2.5°C	-597	-3,227	-2,602	-2,413	-40.6%	-48.9%	-49.7%	-47.7%
Increase temp 5°C	-1,120	-6,693	-5,364	-4,963	-76.2%	-101.3%	-102.5%	-98.2%
Decrease rain 15%	116	543	408	420	7.9%	8.2%	7.8%	8.3%
Increase rain 15%	-67	-341	-257	-261	-4.6%	-5.2%	-4.9%	-5.2%
Per 1° change to 2.5°C	-239	-1,291	-1,041	-965	**-16.2%**	**-19.5%**	**-19.9%**	**-19.1%**
Per 1° change 2.5 to 5°C	-209	-1,386	-1,105	-1,020	**-14.2%**	**-21.0%**	**-21.1%**	**-20.2%**
Per 1% decrease in rain	8	36	27	28	**0.53%**	**0.55%**	**0.52%**	**0.55%**
Per 1% increase in rain	-4	-23	-17	-17	**-0.30%**	**-0.34%**	**-0.33%**	**-0.34%**

Step 5. Evaluate the Effects of Climate

Next, the above incremental effects of changes in climate are applied to the base case scenario and the four climate change scenarios in each AEZ to generate vectors of changes in expected farm incomes from baseline conditions. Because these are expected values, they are interpreted broadly to represent changes in livestock incomes across Ghana. In total, five of these vectors are generated for each AEZ, or 20 in total. Here, "baseline conditions" are defined as the mean precipitation and temperature in the base case scenario; as such, all results presented here are deviations from that baseline. This approach involves two important assumptions:

- Because SM consider precipitation and temperature independently rather than jointly in their fixed changes analysis, the present analysis does not interact these two effects. Instead, the analysis conservatively takes whichever factor—temperature or precipitation—has a more pronounced negative effect on expected income.
- Changes in temperature from the baseline mean sometimes exceed 5°C, and changes in precipitation may be higher/lower than +/-15 percent. In these cases, we cap temperature at 5°C and precipitation at +/-15 percent in order to remain within the bounds of SM's range of analyzed scenarios.

Adaptation to deal with the unavoidable impacts of climate change to manage risks in the agricultural sector is a must. The level of adaptation is an economic problem, constrained by the amount of resource available, yet mitigated also by the expected impacts of climate change on livelihoods.

Adaptation Options

At the Global Track model, adaptation measures in agriculture include (a) agricultural research and efficiency (linked to extension services to farmers); (b) improvements in rural roads; (c) irrigation infrastructure provision; and (d) fish farming, livelihood diversification measures, and marine protected areas.

In Ghana, adaptation options in the agricultural sector must (a) foster links among agriculture, roads, and other infrastructure provision (irrigation, markets, etc); (b) improve links among productivity enhancing research and development with extension service delivery improvements focused on poverty reduction and the inclusion of the most vulnerable; and (c) take into consideration differences in agro-ecological zones, crop composition, and adaptation to likely shifts in production patterns in these zones.

The National Climate Change Adaptation Strategy (NCCAS) provides an overview of the impacts of climate change on different sectors of the Ghanaian economy even up to 2080 by categorizing them as urgent, immediate, and long-term challenges. In this report, additional adaptation options to address climate change impacts have been generated based on discussions held with the directorate of the Ministry of Food and Agriculture; adaptation options recommended by the Global Track modeling study; priority adaptation action programs outlined by the Ghana National Climate Change Adaptation (NCCA) Strategy; and interactions with sector expert participants on the adaptation option strategy workshops on agriculture.

These adaptation options have been coded as high (red), medium (blue) and low (green) priorities Table A-8. For example, increased agricultural research and efficiency (linked to extension services to deliver new crop/livestock to farmers), provision of rural roads to enhance both national agricultural marketing and exports of cash crops, and new irrigation infrastructure are highlighted as high priority as they are the major investment needs to improve agricultural sector productivity.

Table A-8 Adaptation Options in Agriculture due to Climate Change

Major Subsectors in Agriculture	Ongoing major strategies in Agriculture (business-as-usual)	Additional Adaptation strategies due to Climate Change in Agriculture	Priority Code
Cereal Production	Use of drought-tolerant and early maturing crops; shifts in timing for planting to meet early rains; controlled use of chemical fertilizers and integrated pest control; erosion control: bunding, ridges along contours; soil and water conservation measures; water harvesting	▪ Increased agricultural research and efficiency (linked to extension services to deliver new crops/livestock to farmers)	High
		▪ Rural roads provision to enhance both national agricultural marketing and exports of cash crops	High
		▪ Irrigation infrastructure provision	High
		▪ Construction of more dams for irrigation projects in the Savanna region for sustainable water management and subsurface water storage construction	Medium
Cocoa	Development of drought-tolerant, high-yielding, disease-resisting planting materials and support for improved agronomic practices to sustain cocoa production and farmer's livelihoods	▪ Livelihood diversification measures: fish farming and marine protected areas	High
	Planting of drought-tolerant and early maturing crops; reforestation and agroforestry by planting trees within the degraded forest lands	▪ Market infrastructure and market linkages	Low
Root Crops		▪ Agroecological-specific agricultural crop/livestock adaptation needs	Medium
	Soil and water conservation measures; controlled burning; establishing woodlots	▪ More gender-differentiated adaptation needs	
		▪ Crop composition adaptation to shifts in resources between food and cash crops	Low
		▪ Adaptation to social/economic vulnerability	
Land Degradation		▪ Setting up monitoring systems for the climatic and other environmental factors on a regular basis for agriculture	Medium
		▪ Managing water resources efficiently regionally, especially the Volta basin	Medium

Annex 2

Dose-Response for Model Roads

BACKGROUND

The primary focus here is on the direct impacts of potential climate changes on road transportation infrastructure. Nevertheless, many of these effects will be influenced by the environment in which the infrastructure is located. For example, increased precipitation levels will affect moisture levels in the soil and hydrostatic buildup behind retaining walls and abutments and the stability of pavement subgrades. Runoff from increased precipitation levels will also affect streamflow and sediment delivery in some locations, with potentially adverse effects on bridge foundations. And sea level rise will affect coastal land forms, exposing many coastal areas to storm surge as barrier islands and other natural barriers disappear.

Projected warming temperatures and more heat extremes will affect road infrastructure. Periods of excessive heat are likely to increase wildfires, threatening communities and infrastructure directly. Longer periods of extreme heat may compromise pavement integrity and cause thermal expansion of bridge joints, adversely affecting bridge operation and increasing maintenance costs.

The frequency, intensity, and duration of intense precipitation events are important factors in design specifications for road transportation infrastructure. Projected increases in intense precipitation events will necessitate updating design specifications to provide for greater capacity and shorter recurrence intervals, increasing system costs. The most immediate impact of more intense precipitation will be increased flooding of coastal roads. Expected sea level rise will aggravate the flooding because storm surges will build on a higher base, reaching farther inland. Low-lying bridge and tunnel entrances for roads will also be more susceptible to flooding, and thousands of culverts could be undersized for flows. Engineers must be prepared to deal with the resulting erosion and subsidence of road bases, as well as erosion and scouring of bridge supports. Interruption of road traffic is likely to become more common with more frequent flooding.

The vulnerability of road transportation infrastructure in Ghana is a real challenge to national development and a deterrent to national poverty reduction strategies. It is important to identify the appropriate adaptation options and integrate these options into national budgeting and planning.

The standard design of infrastructure should be based on a complete understanding of the local climatic, economic, and social conditions and needs. For example, road design for rural farming areas should acknowledge that roadsides provides a marketing possibility for small- and medium-size farmers to sell their crops, vegetables, and fruit. In addition, new infrastructure work, design standards, training programs, and maintenance should address specific local communities' preferences and needs. Ghana's government officials suggested that infrastructure design standards should also consider the specific nature and requirements of different roads (highway, urban, and rural roads) and the relevant engineering parameters of each specific type of road or other transportation infrastructure components, such as thickness, weight, and appropriate materials.

Dose-Response Model

Table A-9 below summarizes the potential climate changes and the associated vulnerability of Ghana's road transportation system.

Paved roads

Modeling paved roads involves two basic steps as seen in Equation 1 below: (1) estimating the lifespan decrement that would result from a unit change in climate stress, and (2) estimating the costs of avoiding this reduction in life span. For example, if a climate stressor is anticipated to reduce the life span by 2 years or 10 percent, and the cost to offset each percent of reduction is equal to a percentage of the current maintenance cost, then the total would be (10%)(current maintenance cost) to avoid decreasing the current design life span.

Equation 1 $$MT_{ERB} = (L_{ERB})\ (C_{ERB})$$

Where:

MT_{ERB}: Change in maintenance costs for existing paved roads associated with a unit change in climate stress

L_{ERB}: Potential change in life span for existing paved roads associated with a unit change in climate stress

C_{ERB}: Cost of preventing a given life-span decrement for existing paved roads.

To estimate the reduction in life span that could result from an incremental change in climate stress (L_{ERB}), we assume that such a reduction is equal to the percent change in climate stress, scaled for the stressor's effect on maintenance costs (Equation 2).

Equation 2 $$L_{ERB} = (SMT)$$

Where:

S: Change in climate stress (i.e., precipitation or temperature)

$BaseS$: Base level of climate stress with no climate change

SMT = Percent of existing paved road maintenance costs associated with a given climate stressor

(i.e., precipitation or temperature)

Unpaved road calculations (direct response methodology)

The change in unpaved road maintenance costs associated with a unit change in climate stress is estimated as a fixed percentage of baseline maintenance costs. In general terms, this approach is summarized by Equation 3.

Equation 3 $$MT_{URR} = M \times B_{URR}$$

Where:

MT_{URR}: Change in maintenance costs for unpaved roads associated with a unit change in climate stress

M: Cost multiplier

B_{URR}: Baseline maintenance costs

Adaptation Options

Infrastructure adaptation strategies include both hard infrastructure adaptation strategies and soft infrastructure adaptation strategies. Hard infrastructure adaptation strategies mean hardening roads and bridges to face expected changes in climate. This hardening can be achieved via investment in infrastructure climate proofing systems. This requires an increase in routine, periodic, and maintenance costs for rehabilitation and upgrade of transportation. Changing the standard designs of these hard infrastructures is necessary to consider the expected climate change factors (e.g. temperature and precipitation increases). The soft infrastructure part of climate change adaptation includes training programs, decision support tools, and outreach activities. Table A-9 below shows workshops results on priority setting for road adaptations in Ghana.

Table A-9 Adaptation Options-Transportation (Road)

ROAD MAINTENANCE OR CONSTRUCTION ACTIVITIES	ADAPTATION OPTIONS (Temperature Increases)	PRIORITY	ADAPTATION OPTIONS (Increase in Intense Precipitation Events)	PRIORITY
MAJOR ROAD PROGRAMS: Routine Maintenance				
Grading & Patching			Change in infrastructure design and materials	Low
Bridge & Culvert Cleaning (for earth, gravel and paved roads)	Make provision for expected temperature changes during design of bridges	Low	Expansion of systems for monitoring scour of bridge piers and abutments Design for more frequent flooding Lessen threat of bridge becoming a pinch point causing backwater by making emergency bypass channels	High
Desilting			Increase maintenance removing sediment deposits	High
Paved Roads Pothole Patching	Development of new, heat-resistant paving materials	Medium	Higher crown paved road increases runoff Better surface drainage Pave shoulders to lead runoff away from base materials Use flatter shoulders and more material to aid drainage way from section Increase maintenance to repair potholes and cracks Use geo-fabric for waterproofing	High
Green Area Maintenance	Greater use of heat-tolerant street and highway landscaping	Medium		
MAJOR ROAD PROGRAMS: Periodic Maintenance				
Earth Roads Improvement of Soft-spots			Change in infrastructure design and materials	
Gravel Roads Regravelling	Binding course material to suppress dust levels	High	Increase crown of road to aid drainage Increase surface drainage Increase maintenance due to faster erosion of gravels	High
Paved Roads				
Asphaltic Concrete Overlay	Development of new, heat-resistant paving materials	High	Higher crown paved road increases runoff Better surface drainage Pave shoulders to lead runoff away from base materials Use flatter shoulders and more material to aid drainage way from section Increase maintenance to repair potholes and cracks Use geo-fabric for waterproofing	High
Drainage: Drain Construction			Improve hillside drainage Alternative slope stability measures Addition of slope retention structures and retaining facilities for landslides Increases in standard drainage capacities Increased maintenance	High
Pipe-Culvert Construction			Change design parameters to account for expected increase in intensity of precipitation events Redesign inlets to accommodate more water Increased protection on outfall	High
MAJOR ROAD PROGRAMS: Development Works (Major Improvements and New Construction)				
Major Rehabilitation	Changes in infrastructure design standards	High	Change design parameters to account for expected increased precipitation events Redesign inlets to accommodate more water Increase protection on outfall	High
Reconstruction works	Shifting construction schedules to cooler parts of the day	Low	Higher crown paved road increases runoff. Better surface drainage Pave shoulders to lead runoff away from base materials Use flatter shoulders and more material to aid drainage way from section Increase maintenance to repair potholes and cracks Use geo-fabric for waterproofing	High
Bridges	Make provision for expected temperature changes during design of bridges	Low	Expansion of systems for monitoring scour of bridge piers and abutments Design for more frequent flooding Lessen threat of bridge becoming a pinch point causing backwater by making emergency bypass channels Greater use of sensors for monitoring water flows Restriction of development in floodplains	High

Annex 3

IMPEND Model for Energy and Water

BACKGROUND

Despite the fact that Ghana has considerable surface and groundwater resources, water resources will be hit hard under climate change. Under a changed climate, lower precipitation, enhanced evaporation, and more frequent droughts will diminish water availability in the Lake Volta reservoir. Additionally, the Akosombo Dam, which typically provides about 70 percent of the country's energy needs, produces only 30 percent during periods of low water levels in the dam, posing serious implications for industrialization and private sector development.

Water for domestic use and plant use has become scarcer due to the combined effect of declining rainfall, lowering of the groundwater table, drying streams and wells, and poor water retention capacity of the soils. Since most farmers rely on rainfed agriculture (irrigation is not common in most areas), these factors also contribute to large inter-year variations in agricultural productivity.

Water Supply and Demand

Supply. Groundwater recharge is likely to be reduced between 5 percent and 22 percent by the year 2020 and between 30 percent and 40 percent by the year 2050. This is a particularly noteworthy situation for the upper east region, given that this region has the highest number of dams and dugouts in the country, and economic activities are increasingly related to effective utilization of this infrastructure.

Demand. Pressures from population and a growing economy will lead to significant increases in the consumption of water. For the dry interior Savanna region of Ghana, water demand in 2050 is projected to be about 12 times the current level.

Water scarcity will increase the competitive pressures for basic uses of water, diminish agricultural productivity, increase the risk of waterborne diseases, and have a negative impact on labor availability, productivity, and migration. Several adaptation options are instrumental in helping Ghanaian communities to adapt to such shortages.

Energy

Ghana's energy sector has already shown signs of susceptibility to climate change, particularly the effect of highly variable precipitation patterns on hydropower production. At present, 67 percent of electricity generation in the country is from hydropower and 33 percent is from petroleum-fired thermal generation (Energy Statistics 2006), with a small contribution of less than 1 percent from small-scale solar systems.

The 1980–83 drought not only affected export earnings through crop losses, but also caused large-scale human suffering and called into question the nation's continued dependence on hydroelectric power. As a result, the development of petroleum-fired thermal plants is now viewed as an energy security necessity in Ghana. The current rate of electrification presents a challenge—providing energy in a suitable form to a large population, primarily rural but increasingly urban, while at the same time minimizing greenhouse gas emissions.

System losses in electricity distribution are about 25 percent, with wastage in the end-use of electricity also estimated at about 30 percent. Losses in energy supply and inefficient use of energy contribute to the high levels of energy consumption. Higher ambient temperature levels due to climate change are a contributing factor to the increased transmission losses.

Higher temperatures are giving rise to increased electricity consumption for air conditioning systems.

In the water sector, the Ghana EACC team propose that climate change adaptation strategies include investment in additional reservoir capacity. These strategies consider demand for water spatially among various agroecological zones and across time. For example, demand for irrigation means providing water supply to meet seasonal water demand for irrigation. These adaptation strategies include projects on flood control design and construction. A high level of coordination between power production (hydro) objectives and plans and agricultural sector investment and expansion plans will help provide a successful adaptation strategy. Other climate change adaptation strategies include rain harvesting, water desalination, and water reuse (recycling) programs and projects. Adaptation strategies in the water sector focus on a wide range of remedies and solutions that not only consider large-scale projects, but also provide medium- and small-scale measures such as building ponds and small water storage (dug outs) capabilities to allow communities larger control and management over water resources. Training programs, decision support systems, and outreach programs on water management, water re-use, and water storage should be included in order to reach sustainable outcomes.

To adequately respond to climate change, enhanced water management capabilities are needed in Ghana. Adaptation strategies use an integrated framework in the analysis of the tradeoff between water use for hydroelectric generation, agriculture, municipal, and industrial uses. This integrated framework means using a watershed approach rather than a sector approach to allocate water optimally between the various uses under climate change scenarios. Adaption strategies should also consider water and energy efficiency.

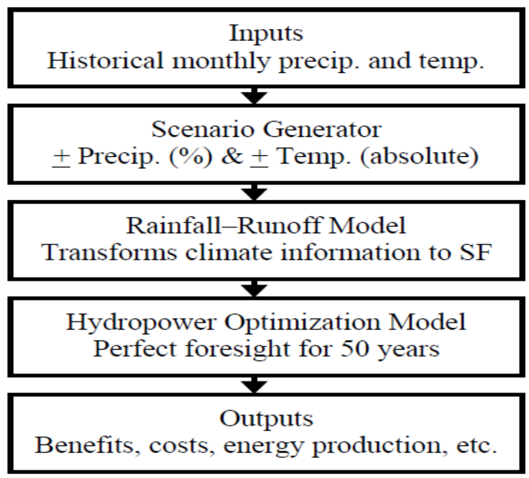
IMPEND Model Structure

The allocation of surface water resources to hydropower production and energy employed a planning model developed for Ethiopia, the IMPEND model (Investment Model for Planning Ethiopian Nile Development). IMPEND is a deterministic perfect foresight water resources system optimization model, written with the general algebraic modeling system software (GAMS 2005; accessible at: <<http://www.gams.com>>; Block and Strzepek 2009).

IMPEND inputs include measurements or estimates of monthly stream flow, net evaporation at each reservoir, electricity demand, and discount rate, along with reservoir attributes such as storage, maximum head, volume, and surface area. These and GCM inputs—such as predicted river runoff and river basin evaporation—are then used to compute the aggregate water inflow into the hydro units of the model minus evaporation. This requires measurements or estimates of monthly stream flow, net evaporation at each reservoir, and discount rate, along with reservoir attributes such as surface area of each reservoir, design head, and peak energy output.

Output includes a time series of energy generation and associated project costs. Hydropower simulation was done using a hydropower planning model developed for Ethiopia. The IMPEND simulation required estimates of monthly flow and net evaporation from the hydrologic model CliRun. The CliRun model was used to estimate flow into the hydropower generation facilities for the four future climate realizations as described above. These flow estimates were used in IMPEND to estimate the potential power generation available under these hydrologic conditions. All other assumptions and conditions were identical with the baseline. Operating assumptions, surface areas of the reservoirs, and so on were all held constant; only influent flow changed. The output, combined with other technical data, is then used to estimate the aggregate annual energy production for the baseline and climate change scenarios (Figure A-4). The results are fed into the CGE model to simulate climate change impacts. Optimization of electrical energy in IMPEND is formulated around the head level in each reservoir. All operational aspects are nonlinear functions of head, including the reservoir storage, reservoir surface area for determining evaporative losses, the quantity of water released through the turbines, turbine efficiency, and reservoir spilling.

Figure A-4 IMPEND Structure



Source: (Block and Brown 2008)

Adaptation Options

Existing renewable energy programs should be strengthened. Currently, the Ghana Renewable Energy Program promotes the development of renewable energy technologies, particularly biomass and solar energy. There has also been a Liquefied Petroleum Gas (LPG) Program since 1990 to promote the wider use of LPG instead of wood fuels to alleviate deforestation pressures.

The biomass program focuses on the development of a National Wood Fuel Policy to ensure that the production and consumption of wood fuel takes place in an environmentally friendly and sustainable manner. Other strategies call for improved methods for charcoal and firewood production to conserve forest resources, decreased consumption of firewood and charcoal by using more efficient cooking devices, and implementing forest regeneration and afforestation programs.

Ghana receives daily solar irradiation levels ranging from 4 to 6 kWh per square meter, with corresponding peak annual sunshine duration of 1,460 to 2,190 hours. At present, direct solar radiation does not represent a major form of exploited energy in Ghana, and is currently used in niche operations mainly for crop and fish drying using traditional methods. Adaptation initiatives should focus primarily on small-scale, off-grid generation and efficiency improvements. Such initiatives would lead to an improved economic situation for potential beneficiaries. Tables A-10 and Table A-11 summarize the priority setting of climate change adaptation based on the consultations with Ghana government officials and relevant stakeholders.

Table A-10 Adaptation Options for the Energy Sector

Major Energy Supply Sectors	Development Path Interventions	Adaptation Options	Priority
Energy Generation	Increase generation capacity to 5,000 MW by 2015	▪ Upgrade engineering standards and building norms, and retrofit existing infrastructure	Medium
		▪ Upgrade engineering standards and building norms, and retrofit existing infrastructure	High
		▪ Reduce dependence on single sources of energy; opt for more diverse energy mixes to improve overall resilience and adaptability	High
		▪ Take account of predicted impacts of climate change in strategic decisions on energy infrastructure development; for example, avoid excessive reliance on hydropower where stream-flows are expected to be reduced as a result of decreasing rainfall	Medium
	Use gas-based generation for 50% of thermal power-plant production	▪ Promote the development of climate-friendly conversion and curb the use of fossil fuels in energy generation processes	Low
	Increase the renewable energy supply in national energy mix to 10% by 2020	▪ Develop renewable energy resources, particularly biomass, solar, wind energy resources, waste-to-energy, and mini-hydro	High
Demand Management	Achieve 10% savings in electricity consumption through electric power efficiency and conservation measures	▪ Promote policies and measures aimed at promoting energy efficiency in all sectors in order to manage a reduction in emissions without impairing development	High

Table A-11 Climate Change Adaptation Options for the Energy Sector

Major Energy Supply Sectors	Development Path Interventions	Adaptation Options	Priority
Energy Generation	Increase generation capacity to 5,000 MW by 2015	Make energy conversion infrastructure more resilient to extreme climatic events (which may involve upgrading engineering standards and building norms, and retrofitting existing infrastructure)	Medium
		Take account of the potential effects of climate change, and notably of exposure to extreme weather events, in the choice of location for all new infrastructure—and selectively relocate key infrastructure, where it is identified as particularly vulnerable	High
		In electric power networks, create backup capacity and "workaround" solutions, so that a problem at one power generation site does not bring down the whole system	Low
		Reduce dependence on single sources of energy, and opt for more diverse energy mixes to improve overall resilience and adaptability	High
	Use gas-based generation for 50% of thermal power-plant production	Take account of predicted impacts of climate change in strategic decisions on energy infrastructure development; for example, avoid excessive reliance on hydropower where streamflows are expected to be reduced as a result of decreasing rainfall	Medium
		Promote the development of climate-friendly conversion and curb the use of fossil fuels in energy generation processes	Low
	Increase the renewable energy supply in national energy mix to 10% by 2020	Develop renewable energy resources, particularly, biomas, solar, wind, waste-to-energy, and mini-hydro:	High
		Wood fuels: -Support sustained regeneration of woody biomass resources through legislation and fiscal incentive -Promote the establishment of dedicated woodlots for wood fuel production -Promote the production and use of improved and more efficient wood-fuel utilization technologies -Promote the use of alternative fuels such as LPG as substitutes for wood fuel and charcoal -Promote the production and use of other wood fuel energy resources (waste, biofuels)	
		Liquid Biomass Fuels: -Balance biofuel development against food security -Support private sector investments in cultivation of biofuel feedstock, extraction of bio-oil and refining of bio-oil into secondary products by creating appropriate financial and tax incentives	
		Solar, Wind, and Mini Hydro: -Promote the exploitation and use of mini hydro, solar, and wind energy resources -Support indigenous research and development aimed at reducing the cost of renewable energy technologies -Provide tax incentives for the importation of all equipment used in the development of renewable and waste-to-energy projects -Support the use of decentralized off-grid alternative technologies (such as PV and wind) where they are competitive	
		Cross-Cutting Issues: Enact a renewable law to promote development of all renewable technologies through creation of favorable regulatory and fiscal regimes as well as attractive pricing incentives	High
Energy Transmission and Distribution	Improve and modernize distribution infrastructure for efficient service delivery and reduce system losses to 18% by 2015	Make overhead power transmission and distribution infrastructure more resilient to extreme climatic events, if necessary by means of new engineering standards, retrofitting of existing infrastructure, and selective relocation away from the most exposed areas	Low
	Develop an uncongested transmission system by 2015	Take account of the potential effects of climate change, and notably of exposure to extreme weather events, in the choice of location for all new infrastructure	
		Gradually switch to underground rather than overhead transmission lines, in particular to supply power to essential economic and social infrastructure	Low
		Reduce electric power transmission losses (which may be aggravated by higher ambient temperatures) by producing electricity closer to the places where it is used, which implies a switch to a more decentralized electricity production infrastructure	Medium
		In energy networks of all types (including pipeline networks), create backup capacity and "workaround" solutions, so that a transmission problem in one location does not paralyze the whole system	Low
		Closely monitor trends in migration and population resettlement, so as to anticipate future needs at the time of planning investments in new energy infrastructure	High
Demand Management	Achieve 10% savings in electricity consumption through electric power efficiency and conservation measures	Promote policies and measures aimed at promoting energy efficiency in all sectors in order to manage a reduction in emissions without impairing development	High
		Technological Change	Medium
		Tariff changes	Low

Annex 4

DIVA Model for Coastal Zone

BACKGROUND

A number of coastal climate change adaption strategies and measures should be considered, including projects and programs to enhance and encourage coastal protection. These projects include an increase in sea dikes, upgraded ports, construction of river dikes, beach nourishment, and increased investment in maintenance of hard coastal infrastructure components. Beach nourishment is highly recommended because of the importance of beach nourishment to the coastal tourism industry. Upgraded ports would support vital economic activities such as agricultural exports.

Coastal protection should also include soft infrastructure programs and projects, such as training programs, decision support systems, and outreach to coastal communities on climate change risk. The Ghana EACC team is recommending a coastal mangrove protection and management program, investments to reduce coastal sand degradation, and support for the coastal fisheries industry. The coastal mangrove program is necessary to support the tourism industry. The objective of the sand degradation reduction program is to protect the soil near the coast and reduce the risk of soil erosion. Support for aquaculture will enhance both coastal livelihoods and the tourism industry. Adaptation strategies in coastal Ghana should also include programs to transfer appropriate fisheries' technology to enhance preparedness (e.g. early warning systems), increase productivity, and boost efficiency. A subsidized insurance program could provide a safety net for rural communities in coastal zones in Ghana.

Specific to Ghana's coastal fisheries, we recommend programs for a safety net, compensation to catch losses, and a supported insurance program. In addition, diversification of livelihoods will strengthen the coastal economy and discourage immigration of the workforce to other urban communities.

DIVA Model

The DIVA model is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise due to climate change and socio-economic development (DINAS-COAST Consortium, 2006; Vafeidis et al., 2008; Hinkel et al. 2009). DIVA is based on a data model that divides the world's coast into 12,148 variable length coastal segments, based on political, socio-economic and physical characteristics. It associates up to 100 data values with each segment (DINAS-COAST Consortium, 2006; Vafeidis et al., 2005; 2008). In the DIVA model, the coast of Ghana is represented by 22 coastal segments.

DIVA is driven by climate and socio-economic scenarios. The main climate scenario in DIVA is sea-level rise, while coastal population change and GDP growth represent the primary socio-economic scenarios. DIVA downscales the sea-level rise scenarios by combining global sea-level rise scenarios due to global warming with an estimate of the local vertical land movement. These local components vary from segment to segment and are taken from the global model of glacial-isostatic adjustment of Peltier (2000a; 2000b). For segments which occur at deltas, additional natural subsidence of 2mm/year is assumed. Note that human-induced subsidence associated with ground fluid abstraction or drainage may be much greater in deltas and susceptible cities than considered here (e.g., Nicholls, 1995; Ericson et al., 2006; Syvitski et al., 2009). In addition, the impacts of regional sea-level rise are also considered as the sea level measurements in Ghana (i.e., Takoradi station) suggest that the coastal areas of the country are believed to experiencing additional sea-level rise. Note that, while changes in storm characteristics attract widespread concerns in some coastal areas, Ghana does not experience tropical storms which are most likely to change, and we do not consider any changes in storm characteristics (i.e., a climate variability parameter) in this study. To account for the local effect of subsidence in Ghana as demonstrated by the sea level measurements at Takoradi station (Figure 3) and the estimates of subsidence for the Volta delta in Ericson et al. (2006), improved assumptions have been made compared to the global analysis of Nicholls et al. (2010). In this study, an additional 2mm/year was considered in Volta delta and 1mm/year for the remaining sections of the coast.

The flooding of the coastal zone caused by sea-level rise and associated storm surges is assessed for both sea and river floods (i.e. the backwater effect). Taking into account the effects of dikes, flood areas for different return periods from 1-in-1 to 1-in-1000 years are computed. In addition to the mean level change, the present extreme water levels produced during storm surges are simply displaced upwards with the rising sea level. This approach follows the 20th century observations of extreme sea-level rise (e.g., Zhang et al., 2000; Woodworth and Blackman, 2004; Haigh et al., 2008). Based on the experience of Delft Hydraulics (now Deltares), particularly based on its application in the global analysis of Hoozemans et al. (1993), flood protection measures are considered as the adaptation options to respond to flooding and submergence. For practical purposes, in all the subsequent analysis, these defenses are treated as dikes. Since there is no empirical data on actual dike heights available at a global level, optimum dikes heights were estimated for the base year of 1995 using cost-benefit analysis. Based on these dikes, land elevations and relative sea level, the frequency of flooding is estimated over time. The cost of floods is calculated as the expected value of damage caused by sea and river floods based on a damage function logistic in flood depth. In response to beach erosion, nourishment (placing of additional sand onto existing beach/shore areas) is considered.

The social and economic consequences of the physical impacts of sea-level rise are also estimated using DIVA. The social consequences are expressed in terms of a selected indicator of the cumulative number of people forced to migration. This represents the total number of people that are forced to migrate either from the dry land permanently lost due to erosion or they are flooded more than once per year. On the other hand, the economic consequences are expressed in terms of residual damage costs (e.g., costs of land loss and floods) and adaptation costs (e.g., costs of dike construction and upgrade, and beach/shore nourishment). The cost of dry land loss is estimated based on the land-use scenarios and the assumption that only agricultural and unmanaged land is lost. Agricultural land has the lowest use value and it is assumed that if land used for other purposes (e.g., industry or housing) is lost then those usages would move and displace agricultural land or natural areas. The value of agricultural land is a function of income density. The cost of salinity intrusion into river deltas is calculated in terms of the agricultural land affected and the assumption that saline agricultural land has half the value of non-salinised land. The cost of floods are calculated as the expected value of damage caused by sea and river floods based on a damage function logistic in flood depth.

Adaptation costs are estimated for the two planned adaptation options considered: (1) dike (sea or river) building and upgrade, and (2) beach/shore nourishment. Dike costs are taken from the Global Vulnerability Assessment carried out by Hoozeman et al. (1993), which is the most recent global assessment of such costs. The costs of nourishment were derived by expert consultation, and again mainly based on the wide experience of Delft Hydraulics (now Deltares). Different cost classes are applied, depending on how far the sand for nourishment needs to be transported, as this is a significant determinant of such costs. The possible effects of land use policy are also considered by keeping the coastal population constant. This might represent a policy where all land threatened by sea-level rise is not developed (note that this policy is not costed). While the selected options are rather limited and stylised compared to real adaptation choices, they provide useful and consistent cost estimates that illustrate the relative magnitude of costs that Ghana might face given sea-level rise.

Annex 5

Social Dimensions of Climate Change

BACKGROUND

The impacts of climate change—particularly drought, floods, and sea level rise—represent a profound threat to the livelihoods of the poor in Ghana. Households have been coping with climate variability for decades, but projections of climate-change-induced changes in temperature and precipitation bring a new urgency to comprehensive and coordinated solutions that respond to area-specific threats. Ghana is highly dependent on climate-sensitive sectors such as agriculture, which accounts for 32 percent of GDP, as well as forestry and hydroelectric energy. Agriculture is particularly vulnerable due to low levels of irrigation. The northern savannah region bears the brunt of the climate-induced livelihood crisis, since the agriculture sector has already been devastated by desertification, leaving little margin for additional climate stressors. There has been significant out-migration from the region and increased conflict over resources among those who remain. In the transition and forest belts, deficits in the number of rainy days threaten rural livelihoods, though not yet to the point of drought. Rather, there is a shortening of the farming season and gradual fading of the minor season in transition areas. These have direct impacts on agricultural production, water availability, and consequently food security. An increase in seasonal floods indicated by climate change scenarios could also cause significant impacts in highly populated urban and peri-urban areas in Greater Accra, particularly the possibility of disease outbreaks in the "zongo" slums dominated by in-migrants.

The incidence of floods is already high in the coastal and northern savannahs and also along river towns. Ghana's 565-km coastline is inhabited by about a quarter of the country's population, and includes significant physical infrastructure and economic activity. Rising sea levels will impact the coastal zone through shoreline recession, increased flood frequency probabilities, inundation of coastal lands and wetlands, and salinization of surface and groundwater (EPA 2000a). Indigenous fishing communities will be most affected in terms of lost physical assets and livelihoods. Both drought and floods affect disease incidence and food security. Increased heat stress and drought-related deaths—affecting both humans and livestock—are already being experienced in the extreme north of the country. Changes are also expected in the range of some infectious disease vectors. Flooding will increase the range of the mosquito, leading to different malarial strains, and the incidence of parasitic infections may increase.

To complement the other sector and economic studies undertaken within the EACC study in Ghana, a "social component" was developed that used a bottom-up perspective to vulnerability assessment and identification of adaptation investment options. The social component views vulnerability as encompassing both physical and socioeconomic elements. It adopts IPCC definitions of vulnerability as comprising physical exposure, socioeconomic sensitivity, and adaptive capacity components (including levels of skills, institutional "thickness," and degree of market integration).

Methods

The vulnerability assessment included a literature review, identification of select "hotspots" (representing both physically exposed and socioeconomically vulnerable areas), and fieldwork in these areas (including focus group discussions and a small survey of 80 households). The identification of adaptation options comprised a series of three participatory scenario development (PSD) workshops at local/regional and national levels to determine local stakeholders' development visions for the area, their assessment of livelihood and other impacts of climate change in the area, and preferred adaptation options for investment.

Primary data collection employed a combination of qualitative and process tools including participatory rural appraisal (PRA) methods as well as PSD workshops to identify preferred adaptation options of local stakeholders. This methodology uses a range of data collection tools and techniques—including focus group discussions, ranking/scoring exercises, seasonal diagramming, timelines, well-being categorization, as well as semi-structured interviews and key informant interviews with 10 households per site purposively sampled from different well-being tiers—to gather information regarding climate hazards, impacts, and adaptation practices. Household data were collected on assets, sources of livelihood, income and exchange, capital investments, credit, education, illness, access to common property resources, and other variables related to household livelihoods.

A series of PSD workshops were also held. The Phase I national workshop was held in Accra in June 2009, followed by three regional workshops in August 2009. The regional workshops focused on the transition, forest and coastal savannah zones. The Phase II PSD workshop took place in Accra on September 2–3, 2009. Representatives from government, nongovernmental organizations, research institutes, and participants from the regional workshops were invited to attend. The objectives of Phase II were to (a) validate and prioritize the outcomes from previous workshops, especially those focusing on key impacts of climate change and potential adaptation actions needed to address the impacts from the perspective of diverse livelihoods, regions, and vulnerable groups; (b) identify existing and alternative adaptation options that are relevant for different livelihoods; and (c) identify integrated and robust adaptation pathways that prioritize adaptation measures and desired investments in the short, medium, and long term (Bizikova et al 2009).

The PSD workshops—that is, two workshops at the national level and three at the zonal level—provided an opportunity for a range of stakeholders, including government officials, local experts, and representatives to explore the future in a rigorous, creative, and policy-relevant way. In the national workshop, participants were grouped according to the four sociogeographic zones (northern savannah, transition, forest, and coastal savannah), while in the regional/zone participants were grouped according to sectors and livelihood groups. Results from district workshops were summarized during the national workshop to enable a broad-based informed analysis of issues for the country.

The national workshops began with presentations by local experts to characterize current climate and socioeconomic projections for the coming decades, as inputs to participants creating visions of a "preferred future" for 2050. This was followed by considering the specific impacts of climate change on the future vision, and then identifying adaptation options necessary to reach the desired vision. Finally, participants created an adaptation pathway showing diverse priorities for adaptation actions over time. They also identified prerequisites, synergies, and tradeoffs among their adaptation options, and with other known development priorities. The PSD workshops drew from down-scaled climate and poverty scenarios offered as graphic "visualizations" used in handouts, presentations, and posters. The workshops helped identify locally relevant pathways of autonomous and planned adaptation in the context of development choices and decisions. The process allowed for joint assessment of required interventions and distribution of benefits, and also pointed to key political economy issues in adaptation planning and implementation. Local-level PSD workshops followed similar approaches, with some modifications of materials and exercises, depending on the audience.

The PSD approach was particularly effective in identifying multi-causal linkages and drivers of vulnerability in climate-affected regions.

Site selection. Traditionally, Ghana has been divided into six agroecological zones—the Guinea Savannah, Sudan Savannah, the forest savannah or transition zone, the semi-deciduous forest, the rainforest, and the coastal Savannah. This study merges the Guinea Savannah and the Sudan Savannah into one zone, known as the Savannah zone. Also, we merge the semi-deciduous forest and the rainforest into one zone, namely, the forest zone. The districts selected for fieldwork were chosen based on a literature review, and on knowledge of cases that would explain the differential vulnerabilities and adaptation options across the country. Sites were also selected with reference to ongoing NGO and donor initiatives in the area. They are not representative of entire ecological zones, as these zones have micro-ecological, economic, cultural, and political differences. The selected research sites are presented in Table A-12.

Table A-12 Sites Selected for Study

Selected Site	Features	Climate Vulnerabilities	Existing Initiatives
Coastal Savannah Zone Site 1: **Ada-Anyakpor,** in the Dangbe-East (Ada) District Site 2: **Nima** in the Accra Metropolitan Assembly (AMA) *Both sites in Greater Accra Region*	(1) Shows livelihood profiles of fisher folks *Exemplifies the struggles of a coastal community*	Dry climate with increasing rainfall variability and hotter temperatures; sea erosion and tidal flooding	Civic responses present, *e.g. Radio Ada in Dangme East district, coastal zone*
	(2) Hosts most of the urban poor in Accra *Shows relationship between poor urban planning and disaster risk*	Prone to flooding; Increased risk of disease; Poverty and disaster response systems in place; Poor shelter provision and drainage systems	One of the communities included in 1995 Participatory Poverty Assessment
Forest Zone Site 3: **Gonukrom** in Wassa Amenfi West (Asankragwa) District Site 4: **Kamaso** in Wassa Amenfi West (Asankragwa) District *Both in Western Region*	(3) Major cocoa growing area; new frontier for agricultural migrants *Issues of land tenure, economic policy, and migration*	Decreasing rainfall will affect cocoa production; high temps harm agriculture; logging and mining will reduce carbon sinks; economic policy reducing forest cover	Among the communities of the IUCN's Livelihoods and Landscapes Initiative (REDD) WB's Forest Carbon Partnership Facility (FCPF)
Transitional Zone Site 5: **Buoyem** in Techiman District Site 6: **Dzatakpo** in Pru District *Both in the Brong Ahafo Region*	Major food crop zone; migrant receiving region; increasing environmental problems *Urban growth and alternative livelihoods*	Variations in rainfall and temperature to affect production; migration increases land pressure; poverty reduces adaptation	EPA and National Development Planning Council with UNDP piloting district-level planning for CCA in Techiman District
	Inland fishing community *Shows livelihoods of fishermen and fish mongers*	Effects of climate on lake Volta; decreasing fish stocks and adaptation by fishing communities; human capital and adaptable livelihoods	No existing initiative
Northern Savannah • Site 7: **Boayini** (Guinea Savannah) in East Mamprusi District *in Northern Region*	Fragile environment *High poverty incidence; female outmigration to cities*	Highly variable weather and agriculture Environmental bankruptcy Resilience of households	Among the communities in which CARE-Ghana is supporting local-level adaptation to climate variability and change in Northern Ghana
• Site 8: **Tetauku** (Sudan Savannah) in Bawku East District in the Upper East Region	Dry environment *Highest poverty incidence in Ghana; agrarian economy; high out-migration*	Highly variable weather and agriculture; environmental bankruptcy; sensitivity of households	Included in 1995 WB Participatory Poverty Assessment

Key Findings on Sources of Vulnerability

Vulnerability was found to stem from a number of factors. These included elements of physical location; economic geography/regional development levels; socioeconomic status; and social differentiation, including migrant status and gender.

Physical Geography. Physical location and hazard proneness greatly affect household vulnerability, as in the drought-prone areas that are chronically exposed to low rainfall. Just as asset depletion occurs in a chronic form at the household level, at the area level too, repeated hazard events can reduce a region's resilience to climate change, particularly when combined with poor resource management. In Ghana's transition zone, cocoa cultivation was formerly widespread in the transition zone, but years of monocropping and unreliable rainfall have led to the abandonment of cocoa farms. A focus group discussion in Buoyem in the transition zone, as well as in the forest zone, reported that over the past 20 years, thick forests had diminished through loss of about 2,000 acres to shrubland, with consequent vulnerable landscape due to delayed rainfall and increased temperature. In coastal areas, sea level rise impacts such as coastal inundation and erosion had displaced the population. Further, the invasion and destruction of coastal wetlands and beaches has affected tourism in the area and harmed biodiversity. Inland fishing livelihoods have been disrupted due to saltwater intrusion into freshwater resources.

Economic Geography and Area Asset Base. Vulnerability can also arise from the existing livelihood systems and policy regimes. For example, single-sector fisheries livelihoods depend on natural resources, and are therefore vulnerable to climate change, as well as to state policies on resource management. Livelihoods across Ghana—from forest-based resources to fisheries and agriculture—depend on clear and effective rule of law regarding natural resource ownership and use rights, and more transparent use of resources. Further, the export-oriented path following by the national government has led to preferential investment in social services and economic infrastructure (including roads). This means that the northern savannah and coastal rural locations in particular have lower resilience and adaptive capacity than the forest and transitional zones, which have received more state intervention to date.

Socioeconomic status. Poverty status (including low physical, financial, and human capital asset levels) lead to extreme vulnerability of households. Common factors here include low levels of education, landholdings, and other productive assets such as boats and outboard motors for fishers. Key vulnerable livelihood groups include smallholder farmers, rural migrant farm laborers, artisanal coastal and inland fishermen and fishmongers, and urban slum dwellers.

Social differentiation including gender and migrant status. Physical hazards have differential effects on diverse groups. Social vulnerability factors identified in Ghana included gender, migrant status, age, and female-headed household status. Vulnerable groups identified through community discussions included the expanding group of rural landless, as well as the elderly and the sick due to their limited adaptive capacity. Women and children left behind—as male adults migrate for employment during drought-related production failures—were identified as vulnerable during and after extreme events. Other vulnerable groups identified included female farmers, communities living on already degraded lands, and pastoral communities who face severe conflicts over access to land. The distribution of land among households is not uniform, reflecting differential access granted by institutions. Access to land is easier in the Guinea savannah zone, with lower population density and non-commercialized systems. The forest and the transition zones have commercialized transactions in land involving sharecropping and rental arrangements. Thus formal and informal institutions structure the extent of individual and group access to resources. Specifically, the gendered nature of the inheritance system, local governance and customary law, and multiple forms of land tenure systems disproportionately harm both women and migrants' adaptive capacity. Rural-rural migrants, for example, forgo income by not planting long-gestation cash crops for lack of secure title in receiving areas. Gender norms in agricultural production also vary by region; for example, women in the northern region are able to cultivate commercially on their own lands acquired from subchiefs, compared to generally family-farmed units in the savannah region.

Adaptation Practices and Coping Strategies

Adaptation practices by households vary according to livelihood group, asset holding level, and to some extent according to zone. In the northern savannah, households cultivated larger farms through agricultural extensification as a form of livelihood insurance. Dry-season gardening with small irrigation systems (hand dug wells and river pumps) was increasing. Women were also taking on more agricultural tasks, rather than remaining limited to sowing and harvesting as in the past. New crop varieties were being used with shorter gestation periods and higher market value, as well as hardy crops such as cassava (in the transition zone). Fertilizer use has increased. Off-farm activities—such as charcoal and fuelwood harvesting—had also increased, as well as shea and dawadawa harvesting and processing. Other practices included outmigration and diversification into livestock rearing. Similar practices were evident in the transition zone, as well as adjusting planting dates to the timing of rains. Forest zone adaptation practices included erosion control measures and use of community volunteer fire officers to manage bushfires. Fishing community members were fishing at night and in deeper lake and river areas, using foreign nets that could cast deep. They were also diversifying to other livelihood activities due to lowered catches. Coastal zone respondents were moving from low-value cereals to vegetables (onions) with higher value. They were also migrating or acting as labor for wealthier boat owners. Multiple livelihoods (combinations of activities) were important for many households across the zones. Social protection and other services were often accessed through private means (chief, family, or church) in contrast to formal sources.

Focus group discussions revealed robust adaptation practices that could be augmented with state support. These included (a) developing drought-resistant short gestation crops; (b) developing small-scale irrigation systems; (c) improving farmer knowledge and supporting integrated farming approaches; (d) promoting woodlots and mangrove regeneration with incentives; (e) conducting research into appropriate, less-expensive building technology; (f) enhancing mechanization of agriculture and encouraging productivity using agrochemicals; (g) refining arrangements for access to land; (h) providing microcredit and skills for diversified livelihoods; (i) encouraging aquaculture, restocking rivers and lakes with fingerlings; (j) providing community social and economic infrastructure, including insurance; (k) providing early warning information; and (l) targeting the poorest households with starter packs and access channels for livelihood diversification.

Adaptation Preferences Arising from PSD Workshops

The PSD workshop process included participants identifying their preferred long-term development vision for the area, as well as expected impacts of climate change on that vision, and the adaptation investments needed to reach toward that vision. Key adaptation investment preferences identified by stakeholders in local and national PSD workshops included social protection measures, health and education services, flood early warning systems, land tenure reform, support to the fisheries sector, training for livelihoods diversification, agricultural research and extension, and integrated soil and water management.

PSD discussions focused on short- (2010–15), medium- (2015–30), and long-term (2030–50) adaptation options. Short-term interventions tended to be less expensive, including advocacy, relief, and support of existing strategies. Medium-term interventions featured infrastructure and institutional development needed to build area resilience, which was identified as the weakest link in Ghanaian adaptive capacity. Long-term interventions were a continuation of “hard” strategies of infrastructure and technology, but with a focus on management capacities to ensure sustainable integrated resource management. Adaptation strategies in the agriculture, water, and services sectors were identified as having strong synergies with each other and with other sectors. Interventions were prioritized for various regions, according to the nature of threats and impacts and vulnerability characteristics.

The PSD workshops revealed broad support for NAPA and related climate strategy priorities in-country, in such areas as agriculture and water resources management, land management, roads, and early warning systems. However, they also revealed stakeholder preferences for investments in governance, social protection, training and education, and land tenure. Training and education were identified as needs not only for livelihood diversification, but also in the area of increased capacity-building in community-based approaches to climate change adaptation and natural resource management. Key pro-poor adaptation investments identified by participants in local PSD workshops included social security measures (safety nets), health services and awareness raising, urban social services and infrastructure, early warning systems, improved tenure security, community-based land administration systems, and skills training. Local participants in the zonal workshops were more concerned with the declining living standards associated with degraded natural resources and lack of public services, whereas national workshop participants looked for investments that would help local areas achieve national goals, often through more expensive adaptation investments that featured limited inputs by local communities. Specific priorities at the local level included a focus on improved agricultural production and land management practices, managing migration, improving conditions for women, and improving governance and institutional structures.

Summary of Findings and Recommendations

In sum, the study found that:

▪Vulnerable groups include those disadvantaged by physical location, gender, asset or migration status, age, and source of livelihood (e.g., fishing community or food crop farmers).

▪Local adaptation preferences are socially differentiated. Further, they are conditioned by factors such as actor cognition, access to information, and channels for social learning.

▪Climate impacts and responses are highly site-specific, and adaptation investments need to be similarly customized, taking into account economic and social trajectories.

▪Both hard and soft adaptation measures are needed for a comprehensive response.

▪Adaptation preferences can be distinguished by local and national levels; in Ghana, local priorities emphasized improved livelihood outcomes and inputs to improved household and area resilience (education, training, and infrastructure and services investments).

▪Past adaptation experience (both indigenous knowledge and introduced best practice) can offer insights, though negative coping strategies must be distinguished from transformative adaptation, whether at the household or area level.

These findings lead to the following recommendations.

▪Employ a focus on assets and capabilities in adaptation strategy and planning.

▪Ensure social protection measures are available for vulnerable populations to smooth consumption, reduce risk, and aid in livelihoods diversification.

▪Scaled-up investments in human capital (education and training), as well as organizational development (user committees, disaster preparedness groups), can help reduce vulnerability in the long and medium terms, as complements to hard infrastructure investments such as irrigation and roads.

▪Facilitating two-way information flows between government and its citizens in the areas of climate data, early warning systems, and available resources can help improve production and marketing, and reduce climate-induced human and livestock mortality and morbidity.

▪Use sociospatial approaches in designing and targeting adaptation programs.

▪Devote attention to governance and decentralized planning processes to ensure users are involved in needs assessment, investment choices, and assessment of service delivery.

A number of measures are required to improve the resilience and adaptive capacity of vulnerable groups. These include improving access to services such as health care and insurance, safe drinking water, affordable energy, and improved access to credit. Accelerated development of rural areas is one way to stem rural-urban migration. To address the needs of migrants already in the urban areas, there is a need to support social safety nets. There is also a need for significant improvements in governance, including decentralization, and increased community participation in decision making. Sustainable resource management and improved land tenure systems are also important in efforts to increase the adaptive capacity of communities. As a result of increased warming, some farmers and fishermen will have to seek alternative livelihoods. There is therefore a need for practical training to build their capacity and enhance their job skills.

A pro-poor approach to adaptation requires an integrated approach that links skills, markets, information, governance, and infrastructure interventions. With attention to these elements, the vulnerability of local communities and poor households can be reduced and their resilience strengthened through transformative measures that build assets and improve long-term adaptive capacity.

Conclusion

Complementary investments in both hard and soft adaptation options are needed to ensure effective use of infrastructure and to meet the needs of the poorest. Adaptation investments in hard infrastructure without complementary investments in policy, service, and extension support will not operate in an optimally efficient manner.

It is important to foster a shift from support for coping strategies for climate shocks at the household level to transformative adaptation strategies that can increase resilience at the household and area level. The poorest are particularly vulnerable to climate shocks, as they do not have stored assets they can use during times of stress. A pro-poor approach to climate change adaptation would look not only at reducing shocks to households, but also engage in transformative adaptation strategies that increase resilience and overcome past biases in subnational investment.

Geographically targeted, multisectoral interventions are needed to reduce the “development deficit” of vulnerable regions. Poverty and sensitivity to climate-related hazards are increasingly concentrated in particular regions within countries. In many cases, poor communities (such as recent urban in-migrants) are relegated to the most marginal areas of the city. Adaptation policies at the national level must take into account the diverse socioecological settings within the country, and devise area-specific interventions that can support the livelihoods of these vulnerable populations. Multisectoral interventions that aim to improve area resilience through reducing the development gap are particularly effective forms of investment, including programming in education, social protection and health, roads, market services, natural resource management, and skills training.

Enabling policies require attention alongside specific sectoral interventions, such as land policy, decentralization, natural resource management, and technology. Climate change adaptation portfolios within countries cannot only be stand-alone investments in infrastructure and services, but also require attention to support for enabling environment policies and mainstreaming of climate concerns in specific sectoral frameworks (e.g., in land policy, decentralization, and technology policies). Without these supportive elements, planners could inadvertently support “maladaptation” that is unable to effectively support sustainable climate resilience. Attention to enabling policies can help reduce latent or open conflict over natural resources, and optimize the impact of discrete adaptation investments.

Annex 6

Computable General Equilibrium (CGE) Modeling

The dynamic computable general equilibrium (CGE) model complements the sector models by providing an economywide evaluation of economic impacts across all sectors within a coherent analytical framework. The CGE model looks at the impact of climate change on aggregate economic performance and considers potential adaptation measures in hydropower, agriculture, transportation, and education.

Model Description

Dynamic CGE models are often applied to issues of trade strategy, income distribution, and structural change in developing countries. They have features that make them suitable for such analyses. First, they simulate the functioning of a market economy, including markets for labor, capital, and commodities, and provide a useful perspective on how changes in economic conditions are mediated through prices and markets. Second, their structural nature permits consideration of new phenomena, such as climate change. Third, they ensure that all economywide constraints are respected. This is critical discipline that should be imposed on long-run projections, such as those necessary for climate change. For instance, suppose climate change worsens growing conditions, forcing Ghana to import food. These imports require foreign exchange earnings. CGE models track the balance of payments and require that a sufficient quantity of foreign exchange is available to finance imports. Finally, CGE models contain detailed sector breakdowns and provide a "simulation laboratory" for quantitatively examining how various impact channels influence the performance and structure of the economy.

In CGE models, economic decision making is the outcome of decentralized optimization by producers and consumers within a coherent economywide framework. A variety of substitution mechanisms occur in response to variations in relative prices, including substitution between labor types, capital and labor, imports and domestic goods, and between exports and domestic sales.

The Ghana CGE model contains 33 commodity groups and 74 activities, including 48 regionally differentiated agricultural and 8 forestry and fishing sectors. Twelve factors of production are identified: six types of labor (unskilled labor, self-employed agricultural labor by zone, and skilled labor), agricultural land in each of the four agroecological zones, agricultural and non-agricultural capital. The agricultural activities and land are distributed across the four main agroecological zones of Ghana (Coastal, Forest, North Savannah, South Savannah) (see Tables A-13 below).

Table A-13 Regional Shares in Agricultural Production by Commodity (Shares in Gross Output Value 2005)

	Coastal	Forest	S. Savannah	N. Savannah	Total
maize	0.21	0.34	0.26	0.18	1.00
rice	0.15	0.40	0.05	0.40	1.00
sorghum	0.00	0.01	0.14	0.86	1.00
yam roots	0.04	0.38	0.24	0.34	1.00
cassava	0.04	0.27	0.44	0.25	1.00
pulses	0.00	0.08	0.10	0.81	1.00
oilseeds	0.08	0.35	0.09	0.48	1.00
fruits	0.15	0.52	0.20	0.14	1.00
vegetables	0.13	0.33	0.36	0.18	1.00
cocoa	0.03	0.67	0.28	0.02	1.00
Other crops	0.47	0.19	0.04	0.30	1.00
Livestock	0.21	0.47	0.24	0.08	1.00
Total	0.09	0.42	0.26	0.22	1.00

Source: 2005 SAM

Table A-14 Commodity Composition of Agricultural Production by Region (Shares in Gross Output Value 2005)

	Coastal	Forest	S. Savannah	N. Savannah	Total
Maize	0.15	0.05	0.06	0.05	0.06
Rice	0.04	0.03	0.01	0.05	0.03
Sorghum	0.00	0.00	0.02	0.15	0.04
Yam roots	0.07	0.15	0.15	0.24	0.16
Cassava	0.05	0.07	0.19	0.12	0.11
Pulses	0.00	0.00	0.00	0.04	0.01
Oilseeds	0.05	0.04	0.02	0.11	0.05
Fruits	0.14	0.11	0.07	0.05	0.09
Vegetables	0.17	0.10	0.17	0.10	0.12
Cocoa	0.06	0.34	0.23	0.02	0.22
Other crops	0.05	0.00	0.00	0.01	0.01
Livestock	0.21	0.10	0.08	0.03	0.09
Total	1.00	1.00	1.00	1.00	1.00

Source: 2005 SAM

Within the existing structure and subject to macroeconomic constraints, producers in the model maximize profits under constant returns to scale, with the choice between factors governed by a constant elasticity of substitution (CES) function. Factors are then combined with fixed-share intermediates using a Leontief specification. Under profit maximization, factors are employed such that marginal revenue equals marginal cost based on endogenous relative prices. Substitution possibilities exist between production for domestic and foreign markets. This decision of producers is governed by a constant elasticity of transformation (CET) function that distinguishes between exported and domestic goods, and by doing so, captures any time- or quality-related differences between the two products. Profit maximization drives producers to sell in markets where they can achieve the highest returns. These returns are based on domestic and export prices; the latter is determined by the world price times the exchange rate adjusted for any taxes. Under the small-country assumption, Ghana faces a perfectly elastic world demand curve at a fixed world price. The final ratio of exports to domestic goods is determined by the endogenous interaction of the relative prices for these two commodity types.

Substitution possibilities also exist between imported and domestic goods under a CES Armington specification. This takes place both in intermediate and final usage. These elasticities vary across sectors, with lower elasticities reflecting greater differences between domestic and imported goods. Again, under the small-country assumption, Ghana faces infinitely elastic world supply at fixed world prices. The final ratio of imports to domestic goods is determined by the cost-minimizing decision making of domestic demanders based on the relative prices of imports and domestic goods (both of which include the relevant taxes). The model distinguishes among various institutions, including enterprises, the government, and five rural and five urban representative household groups in each region. Households and enterprises receive income in payment for the producers' use of their factors of production. Both institutions pay direct taxes (based on fixed tax rates) and save (based on marginal propensities to save). Enterprises pay their remaining incomes to households in the form of dividends. Households, unlike enterprises, use their incomes to consume commodities under a linear expenditure system (LES) of demand. The government receives revenues from activity taxes, sales taxes, direct taxes, and import tariffs, and then makes transfers to households, enterprises, and the rest of the world. The government also purchases commodities in the form of government consumption expenditures, and the remaining income of the government is saved (with budgets deficits representing negative savings). All savings from households, enterprises, government, and the rest of the world (foreign savings) are collected in a savings pool from which investment is financed.

The model includes three macroeconomic accounts: government balance, current account, and savings-investment account. In order to bring about balance in the macro accounts, it is necessary to specify a set of "macroclosure" rules, which provide a mechanism through which balance is achieved. A savings-driven closure is assumed for the savings-investment account, such that households' and enterprises' marginal propensities to save are fixed, and investment adjusts to income changes to ensure that investment and savings levels are equal. For the current account, a flexible exchange rate adjusts in order to maintain a fixed level of foreign savings (i.e., the external balance is held fixed in foreign currency terms). Finally, in the government account, the fiscal deficit is assumed to remain unchanged, with government revenues and expenditures balanced through changes in direct tax rates to households and enterprises. Labor is assumed to be mobile across sectors and fully employed. Under the full employment closure, expanding biofuels production implies reduced use of labor elsewhere in the economy. The assumption of full employment is consistent with widespread evidence that, while relatively few people have formal sector jobs, the large majority of working age people engage in activities that contribute to GDP. The model numeraire is the consumer price index (CPI).

The CGE model is calibrated to a regional 2005 social accounting matrix (SAM) for Ghana jointly constructed by IFPRI and GSS using national accounts, trade and tax data, and household income and expenditure survey data. Trade, income, and factor substitution elasticities are from the Global

Trade Analysis Project (Dimaranan 2006). The model is calibrated so that the initial equilibrium reproduces the base-year values from the SAM.

The features described above apply to a single-period "static" CGE model. However, because climate change will unfold over decades, the model must be capable of forward-looking growth trajectories. Therefore, the model must be "dynamized" by building in a set of accumulation and updating rules; for example, investment adding to capital stock, labor force growth by skill category, and productivity growth. In addition, expectation formations must be specified. Expectations are a distinguishing feature of macroeconomic models. In our CGE model, a simple set of adaptive expectations rules are chosen so that investment is allocated according to current relative prices under the expectation that climate realization in the upcoming year will be an average of recent experience. A series of dynamic equations "update" various parameters and variables from one year to the next. For the most part, the relationships are straightforward. Growth in the total supply of each labor category and land is specified exogenously, while sector capital stocks are adjusted each year based on investment, net of depreciation. Factor returns adjust so that factor supply equals demand. The model adopts a "putty-clay" formulation, whereby new investment can be directed to any sector in response to differential rates of return, but installed equipment remains immobile; that is, a factory cannot be converted into a railroad. Sector- and factor-specific productivity growth is specified exogenously. Using these simple relationships to update key variables, we can generate a series of growth trajectories, based on different climate scenarios.

Climate change is expected to influence the growth and development of Ghana through a series of mechanisms. Four principal mechanisms likely to alter growth and development are considered. These mechanisms are:

1. Productivity changes in dryland agriculture. The influence of climate variables on agricultural productivity will be obtained from the crop models (CLI-CROP). Specifically, the CGE model determines how much land, labor, capital, and intermediate inputs are allocated to a crop as well as an estimated level of production under the assumption of normal climatic conditions. CLI-CROP determines deviations from this level as a consequence of realized climate. The resource allocations determined in the CGE and the deviations obtained from CLI-CROP jointly determine the level of production.

2. Water availability. There are three principal sources of demand for water: municipal needs, hydroelectric power, and irrigation. The river basin models described earlier track water availability under alternative climates. Available water is allocated according to a hierarchy of use. First, municipal demand is satisfied. Second, flow is used to generate hydropower from available dams. Third, flow is used to irrigate cropland. The river basin models pass their results to hydroelectric power planning models, which estimate power output given available flow. In addition, these models can assess the implications of construction of more or fewer dams for electricity output and for flow further downstream. The CGE model incorporates the fluctuations in hydropower production due to variation in river flow. River flow only affects agricultural production if the irrigated area available for planting is greater than the maximum potential area that could be irrigated given water availability constraints.

3. Infrastructure maintenance and upkeep. Changes in temperature and precipitation can influence maintenance requirements for infrastructure, particularly roads. Rainfall or temperature realizations outside of the band of design tolerances are likely to require more frequent or more expensive maintenance costs. In the CGE model, these greater maintenance requirements result in either less rapid expansion in the road network for a given level of spending on roads or an actual shrinkage in the network if the resources necessary to maintain the network are unavailable.

4. Extreme events. Rare but costly events may become more frequent under climate change. In particular, the probability of severe flooding may rise due to greater intensity of rainfall.

Other potential impacts are recognized but not explicitly considered. For example, climate change may alter the incidence of malaria within Ghana, with potential implications for the pattern of economic activity and rates of economic growth. Health-related implications are not considered at this stage.

It is important to highlight that climate change is projected to take place over the course of the next century. The modeling effort only considers the implications of climate change up to 2050, even though climate change is expected to be most severe toward the end of the century. Nevertheless the relatively long time frame considered (40 years into the future) means that dynamic processes are important. Economic development is in many ways about the accumulation of factors of production such as physical capital, human capital, and technology. These factors, combined with the necessary institutional frameworks to make them productive, determine the material well-being of a country.

It is therefore important to note that the dynamic CGE model captures these processes. To the extent that climate change reduces agricultural or hydropower output in a given year, it also reduces income and hence savings. This reduction in savings translates into reduced investment, which translates into future reduced production potential. In the same vein, increased infrastructure maintenance costs imply less infrastructure investment, which further implies less infrastructure both now and in the future. Extreme events, such as flooding, can wipe out economic infrastructure; that infrastructure is gone, both in the period in which the event occurs and all future periods. Generally, even small differences in rates of accumulation can lead to large differences in economic outcomes over long time periods. The CGE model employed is well-positioned to capture these effects.

Baseline

In order to estimate costs imposed by global warming on Ghana, it is necessary to specify a baseline path that reflects development trends, policies, and priorities in the absence of climate change. The objective of specifying such a path is not to forecast the future in a world without climate change. Rather, the baseline path provides a reasonable trajectory for growth and structural change of the Ghanaian economy over about 50 years (the period 2003–50 is modeled) that can be used as a basis for comparison. While the impacts of climate change are many, the analytical objective is to isolate these impacts within the context of a market economy. The CGE model provides the simulation laboratory that allows us to estimate the economic impacts of climate change. Once a baseline path has been determined, we can, for example, run the CGE model forward imposing the implications of future climate on dryland agricultural productivity. Within the model, the decisions of consumers, producers, and investors change in response to changes in economic conditions driven by a different set of climate outcomes.

For example, if climate change is responsible for a precipitous decline in the productivity of crop A but no decline or maybe even an increase in the productivity of crop B, then, holding everything else constant, farmers could be expected to plant more of crop B and less of crop A. This is labeled "endogenous adaptation." In this simplified example, external choices and factors—such as underlying rates of productivity growth, world prices, foreign aid inflows, tax rates, and government investment rules—remain constant (i.e., no exogenous adaptation). By comparing results from the baseline path with those of the revised path, the CGE model provides an estimate of the economywide impact of climate change under the assumption that climate change only impacts dryland agricultural productivity and that all other factors influencing the growth path remain constant – Table A-15 and Figure A-5.

This example is not particularly realistic in that climate change will not uniquely impact dryland agriculture and one expects that some external policies, such as government policies, are likely to be altered in response to a changing climate. However, the example does illustrate the utility of the CGE model as a simulation laboratory and the role of the baseline path. The CGE model permits us to impose specific aspects of climate change within a coherent economic framework. The baseline path provides the frame of reference for evaluating the changes imposed. In this sense, the principal goal in developing a baseline is to present a credible counterfactual. Because comparisons are made with specific changes imposed and everything else held constant, the interesting results—the differences in outcomes between the experiment and the baseline—are likely to be relatively consistent across a fairly broad family of baseline paths. In sum, we do not, in most cases, expect enormous sensitivity of results to the specification of the baseline path.

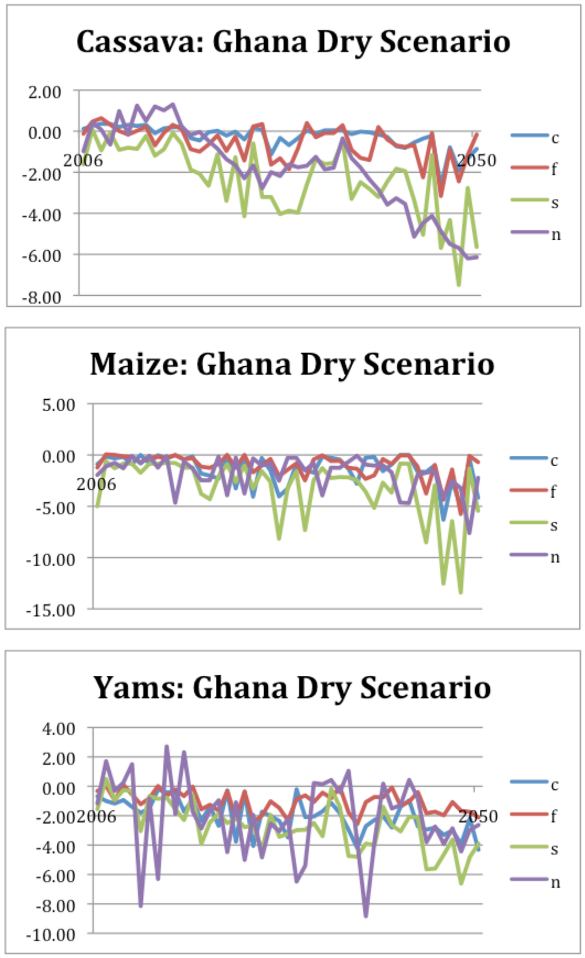
Results will be somewhat more sensitive to the trajectory of baseline variables that are also policy variables. In the next section, potential strategic options for adapting to climate change are presented. Augmenting irrigated area figures among these options. If the baseline plan were to expand irrigation up to the limits of land or water availability, then a potential policy option would be to consider a less aggressive irrigation expansion policy. From this example, it follows that one should take particular care in the selection of the baseline path for potential policy variables.

Table A-15 Average, Maximum, and Minimum Annual Yield Deviations from No-CC Base 2006–50 (Percent)

		csiro: Global Dry			ncar: Global Wet			ipsl: Ghana Dry			ncarp: Ghana Wet		
		ave	max	min	ave	max	min	ave	max	min	ave	max	min
cassava	c	-0.25	0.69	-1.47	0.27	0.95	-0.87	-0.27	0.36	-2.67	-0.09	0.48	-0.79
cassava	f	-0.58	0.16	-1.53	0.16	2.03	-1.78	-0.56	0.63	-3.16	-0.39	0.31	-1.73
cassava	s	-0.60	0.43	-2.11	-2.17	2.47	-7.61	-2.33	0.09	-7.49	0.02	2.61	-3.95
cassava	n	-0.51	1.05	-2.71	-8.64	-1.79	-16.19	-1.81	1.30	-6.20	3.01	5.89	0.35
Maize	c	-0.55	0.02	-2.58	-0.73	0.04	-2.69	-1.37	0.00	-6.31	-0.01	0.60	-0.67
Maize	f	-0.24	0.10	-1.29	-0.57	0.69	-4.70	-1.03	0.06	-5.75	-0.03	0.76	-1.08
Maize	s	-0.94	-0.07	-4.96	-1.63	4.36	-9.10	-3.19	-0.62	-13.40	-0.38	4.21	-5.80
Maize	n	-0.95	0.43	-5.48	-0.30	0.94	-1.16	-1.80	-0.08	-7.61	-0.01	1.37	-1.14
potato	n	-1.07	-0.24	-2.99	1.90	3.66	-0.99	-2.55	-0.93	-6.21	1.49	2.59	0.00
sorghum	c	-0.15	0.65	-1.20	0.57	1.48	0.00	-0.84	0.07	-2.97	-0.22	0.48	-0.86
sorghum	f	-0.64	1.05	-1.75	0.67	4.29	-4.44	-0.65	3.74	-3.72	-0.39	1.15	-3.83
sorghum	s	-0.30	0.32	-1.72	0.52	2.07	0.00	-0.64	-0.01	-3.25	-0.58	-0.02	-2.93
sorghum	n	-0.30	0.27	-2.44	0.11	0.79	-0.11	-0.54	-0.02	-3.35	0.01	0.44	-0.41
soybeans	c	-0.75	1.70	-2.35	0.62	2.90	-0.62	-1.90	-0.36	-6.43	-1.22	0.07	-2.68
soybeans	f	-2.70	0.77	-6.78	1.46	4.63	-2.00	0.90	4.37	-1.81	-1.99	0.90	-7.94
soybeans	s	-2.72	0.09	-5.97	1.02	2.68	-0.72	-1.90	0.39	-5.58	-2.57	0.22	-5.77
soybeans	n	-0.91	0.05	-4.30	-0.14	0.58	-1.05	-0.91	-0.08	-4.93	-0.13	0.66	-0.87
Yams	c	-1.41	0.35	-5.72	-1.37	0.70	-3.49	-2.00	-0.21	-4.32	-0.55	1.37	-3.25
Yams	f	-0.74	1.00	-3.58	-0.96	1.30	-2.95	-1.06	0.11	-2.58	-0.09	2.64	-3.52
Yams	s	-1.32	0.73	-3.76	-3.35	3.76	-6.34	-2.68	0.49	-6.62	-2.12	1.15	-5.66
Yams	n	-2.72	-0.64	-7.52	-2.48	7.56	-9.95	-2.13	2.71	-8.84	2.03	8.68	-1.51

C = Coastal, f = Forest, s = South Savannah, n = North Savannah

Figure A-5 Examples of Annual Climate Change Impacts on Yields 2006-50



Source: Cli-Crop Simulations

C = Coastal, f = Forest, s = South Savannah, n = North Savannah

The impact of climate change on crops is estimated using the Cli-Crop model. The effects of the atmosphere are modeled indirectly in the soil layer through the extraction of ET and the infiltration into the soil layers. The model uses the soil properties and precipitation amount to calculate the infiltration using the USDA curve number method. Then the model calculates the soil moisture in each soil layer. The model then calculates the amount of moisture allowed to percolate into the deep soil layers. The water table is then measured and a yield is calculated. Since CliCrop runs on a daily timescale, total daily precipitation data is required in millimetres per day. The historic precipitation data that is currently built into the model comes from the Collaborative Historical African Rainfall Model (CHARM). The CHARM database contains 36 years (1961–96) of daily historic rainfall for all of Africa estimated by satellite and rain gauge data (Funk et al. 2003). CHARM database information is used to calibrate the reference equation for each crop available from the Food and Agriculture Organization (FAO) CROPWAT database in Africa. Crops included in Cli-Crop are maize, sorghum, millet, rice, beans, groundnuts, cassava, horticulture, sugar cane, cotton, tobacco, sesame, cashews, coconut, and vegetables. When a crop is not included in Cli-Crop, the closest crop in terms of bio-characteristics is used to approximate its yield impact; for example, cassava is usually used to approximate yams due to the similarity between the two crops' bio-characteristics. See mapping from Cli-Crop models to CGE crop activities in Figure A-6. CGE and partial equilibrium cost summary for climate change impacts and adaptation are presented in Table A-16.

Figure A-6 Mapping from CLI-CROP Models to CGE Crop Activities

		CLI-CROP Model					
		Maize	Potato	Sorghum	Cassava	Yam	Cocoa
CGE Model Activity	Maize	X					
	Rice		X				
	Sorghum			X			
	Cassava				X		
	Root Crops					X	
	Pulses	X					
	Oilseeds	X					
	Fruits				X		
	Vegetables	X					
	Cocoa						X
	Other Crops	X					

Table A-16 Cost Summary for Climate Change Impacts and Adaptation (Below)

Sector	Impacts ($ millions)[a] Partial Equilibrium	General Equilibrium	Adaptation ($ millions)[a] Objective of Adapt. Program	Partial Equilibrium	General Equilibrium	Comments
Agriculture	> 34	-80 to 122	Govt program		236 to 765	
Coastal	12–143					1)
Flood Protection						1)
Transport	129–142	-1.7 to 630	Optimization		-	2)
Hydropower	31–89	32 to70	Govt program	67	67	
Other sectors					0 to 765	
Sectors included	Agric, Coastal Transport, Hydro	Agric, Transport, Hydro		Coastal Transport, Hydro	Agric, Transport, Hydro	
Economy-wide	300-400 (mid-range)	236 to 765			236 to 765	

Notes:

a. Annual average amount over period 2010–50 (constant 2005$).

b. Impact column: (-) indicates climate change damage in the absence of adaptation interventions.

c. Adaptation column: CGE figures show minimum and maximum adaptation expenditure across the different adaptation simulations. The adaptation strategies aim to restore aggregate absorption to the baseline, rather than to restore each "sector" to the baseline.

d. Comments: 1) Coastal and flood protection not included in general equilibrium analysis, because DIVA results indicate that costs exceed benefits; 2) Road infrastructure adaptation in the CGE analysis assumes change in road design standards within the fixed baseline road infrastructure budget (hence no additional adaptation expenditure)