



Making Economic Sense of Adaptation in Upland Cereal Production Systems in The Gambia

Momodou Njie, Bernard E. Gomez, Molly E. Hellmuth, John M. Callaway, Bubu P. Jallow, and Peter Droogers

AIACC Working Paper No. 37
August 2006

Direct correspondence to:
Momodou Njie, Blue Gold Solutions, The Gambia, njaaye@netscape.net and
Bernard Gomez, Department of Water Resources, The Gambia, be63gomez@yahoo.co.uk

An electronic publication of the AIACC project available at www.aiaccproject.org

AIACC Working Papers

Distributed by:
The AIACC Project Office
International START Secretariat
2000 Florida Avenue, NW
Washington, DC 20009 USA
www.aiaccproject.org

AIACC Working Papers, published on-line by Assessments of Impacts and Adaptations to Climate Change (AIACC), is a series of papers and paper abstracts written by researchers participating in the AIACC project. Papers published in *AIACC Working Papers* have been peer reviewed and accepted for publication in the on-line series as being (i) fundamentally sound in their methods and implementation, (ii) informative about the methods and/or findings of new research, and (iii) clearly written for a broad, multi-disciplinary audience. The purpose of the series is to circulate results and descriptions of methodologies from the AIACC project and elicit feedback to the authors.

The AIACC project is funded by the Global Environment Facility, the Canadian International Development Agency, the U.S. Agency for International Development, and the U.S. Environmental Protection Agency. The project is co-executed on behalf of the United Nations Environment Programme by the global change SysTEM for Analysis Research and Training (START) and The Academy of Sciences for the Developing World (TWAS).

Assessments of Impacts and Adaptations to Climate Change (AIACC) seeks to enhance capabilities in developing countries for responding to climate change by building scientific and technical capacity, advancing scientific knowledge, and linking scientific and policy communities. These activities are supporting the work of the United Nations Framework Convention on Climate Change (UNFCCC) by adding to the knowledge and expertise that are needed for national communications of parties to the convention and for developing adaptation plans. AIACC supports 24 regional assessments in Africa, Asia, Latin America and small island states in the Caribbean, Indian and Pacific Oceans with funding, mentoring, training and technical assistance. More than 340 scientists, experts and students from 150 institutions in 50 developing countries and 12 developed countries participate in the project.

For more information about the AIACC project, and to obtain copies of other papers published in *AIACC Working Papers*, please visit our website at www.aiaccproject.org.

Making Economic Sense of Adaptation in Upland Cereal Production Systems in The Gambia¹

Momodou Njie, Bernard E. Gomez, Molly E. Hellmuth, John M. Callaway, Bubu P.
Jallow, and Peter Droogers

1. Introduction

The Gambia, 13–14°N, 13.75–17°W, lies in the Sahel region, where rainfall is directly linked to the meridional position of the Inter-Tropical Discontinuity (ITD), and highly sensitive to perturbations of the global monsoon circulation. To cope with seasonal variability associated with such perturbations, Gambian farmers have traditionally used a number of strategies, but how successful these are is open to debate, considering rural-urban migration trends in the past three decades. In the face of imminent threats from climate change, adaptation strategies inspired/informed by past and current coping strategies are reported in the Gambia's Initial National Communication (GOTG, 2003), but their performance remains to be evaluated in terms of economic viability, and/or impact on national food security.

In this paper, SWAP-WOFOST is used in combination with CEREBAL to investigate the impact of climate change on the Gambia's cereal balance under different

¹ The research reported in this paper was supported by grant number AF47 from Assessments of Impacts and Adaptations to Climate Change (AIACC), a project that is funded by the Global Environment Facility, the Canadian International Development Agency, the U.S. Agency for International Development, and the U.S. Environmental Protection Agency and co-executed on behalf of the United Nations Environment Programme and by the Global Change SysTem for Analysis, Research and Training and The Academy of Sciences for the Developing World. Correspondence regarding this paper should be directed to Momodou Njie, njaaye@netscape.net and Bernard Gomez, be63gomez@yahoo.co.uk.

management options. Most significantly, the analysis looks into the economic efficiency of specific management options, subject to social and political acceptability.

2. Cereal Production in the Gambia

Before and after independence in 1965, agricultural policy in the Gambia was primarily driven by the need to generate foreign exchange to pay for goods and services required for economic development. Over the years, this paradigm was reinforced by buoyant world market prices for groundnuts and cheap food prices (Carney, 1986) and only began to lose ground after protracted drought, and economic hardship experienced by farmers in the last two decades. The gradual move away from cash to cereal crops is clearly shown in agricultural statistics (DOP, 2001, 2003, 2005). Cereal production is mainly for consumption, but surplus production by individual *dabada*¹ is sold off on local grain/cereal markets. Cereals grown include rice (*Oryza sativa*), millet (*Pennisetum typhoides*), sorghum (*Sorghum bicolor*), and maize (*Zea mays*), with millet accounting for nearly 60% of area planted and slightly more than 50% of total cereal production (DOP, 2005).

Figure 1 is an elevation map showing the dominance of the River Gambia over the country's geomorphology. Indeed, the River Gambia divides the country into two strips of land no wider than 30 km at any transect. Over 48% of the total land area of the Gambia is below 20 m above mean sea level, and nearly one-third of the country is at or below 10 m above sea level. In general, elevation increases with axial distance from the river. Geomorphological units are described as lowland and uplands. Weathered tropical soils found in the uplands are not very fertile but are well drained. In contrast, fine-

textured soils of the lowlands are poorly drained. This juxtaposition of topography, pedology, and hydrology leads to spatial differentiation of cereal cultivation areas. In general, the River Gambia valley and adjacent swamps are used to cultivate rice (*Oryza sativa*), whereas the plateau is the center for millet (*Pennisetum typhoides*), cultivation.

Traditional agricultural system depends on extensive land use, using little agricultural input. To this effect, successful crop production is dependent on rainfall and favorable environmental conditions. Farmers' vulnerability is systemic and inextricably linked to climate variability, natural soil fertility, and economy-wide policy framework. A sharp and significant drop in average rainfall in the Gambia since the late 1960s has put tremendous pressure on crop production. Lowland rice production, in particular, is under heavy pressure from reduced flood duration and frequencies, saline intrusion, soil acidification, and deposition of sediments eroded from uplands. To fix some ideas, protracted drought and saltwater intrusion in cropland areas have resulted in a 50% decline in the area under rice cultivation (DOP, 2001). Declining soil fertility in uplands is forcing fundamental changes in production such as the use of marginal land, reduced fallows, and deforestation to compensate for low productivity. Although tidal irrigation in lowlands and introduction of improved rice cultivars represent opportunities for increasing total cereal production, water still remains the limiting factor to expansion. Njie (2002a) and, more recently, Verkerk and van Rens (2005), demonstrate the environmental and economic risks of expanding irrigation schemes under natural flow conditions in the River Gambia.

Rural-urban migration of able-bodied youth, contributing to the depletion of the labor force in the rural economy, is somewhat mitigated by technical innovation (e.g., seeders) and diffusion.

3. Adaptation Strategies

In response to climate hazards, farmers have experimented and adopted a raft of strategies to cope with erratic rainfall patterns. An insightful study by Jallow (1995) divides these into (1) risk aversion and (2) risk management strategies. The first category includes crop diversification, crop selection, and plot dispersal. If these fail to provide adequate insurance, farmers, depending on their circumstances, sell off assets, use kinship networks, government assistance in the form of food aid, and harvest natural forest food, to get over the period of hardship.

Cole et al. (2005) report adaptation strategies at government level as (1) sustained support to farmer risk-aversion strategies through appropriation and dissemination of high-yield cultivars, (2) providing engineering and technical leadership in land rehabilitation/conservation, and water control; (3) providing scientific advice in the form of seasonal rainfall forecasting; and when all these fail, (4) providing disaster relief with the assistance of relevant United Nations (UN) agencies, multilateral institutions, and nongovernmental organizations.

Although these strategies worked sufficiently well in the past, a critical evaluation, in the context of climate change and socioeconomic trends, casts doubts on the prospects of some of these strategies. The subsisting problem is how to maintain or increase production under adverse conditions. Limiting constraints include further decline

in rainfall, per capita availability of land, land degradation, widespread poverty, and social mutations.

Our point of departure in this study is the understanding that crop production may be increased by (1) increasing cultivated area and/or (2) increasing crop yields.

Through a screening and integration process of previously proposed adaptation options (Jallow, 1995; GOTG, 2003), we identify (1) crop breeding/selection, (2) crop fertilisation, and (3) irrigation, as the most comprehensive, no-regrets, flexible strategies to improve crop yields. The main argument in favor of crop breeding/selection is that of probable decline in rainfall and increased variability. On the other hand, promotion of crop fertilization as an adaptation strategy is influenced by continuous decrease in available prime land and concurrent degradation of arable land. Moreover, land that requires some amendments represents the second largest class of agriculturally suitable land (NEA, 1997). Irrigation provides a sorely needed means of mitigating impacts of spatial and temporal variability of rainfall and offers the potential for extending a growing season and expanding total cultivated area. Except perhaps for irrigation of upland cereals, these strategies are not entirely new. What is novel about our restatement of these strategies is the systematic, rigorous, and quantitative approach used in this study.

4. Analytical Framework

The analytical framework used in this study, shown schematically in Fig. 2, is built around two key components: (1) crop modeling and (2) economic feasibility analyses, using SRES A2 forcing and outputs from HadCM3 and ECHAM4 global circulation

models (GCMs) adjusted to The Gambia's climate. Every effort is made to ensure that socio-economic scenarios prescribed are consistent with SRES A2.

4.1 Climate scenarios

Outputs from the Max Planck Institute, and Hadley Centre GCMs, ECHAM4, and HadCM3, respectively, for the A2 IPCC SRES scenarios² (IPCC, 2000), were adjusted for use in this study. Details of this procedure known as downscaling can be found in Gomez et al. (2005).

Both GCMs project average temperature rise of 3 to 4°C by 2100, but differ significantly in precipitation/rainfall projections. Whereas ECHAM4 shows no significant change in mean rainfall, and some increase in extreme values, HadCM3 shows a drastic drop in rainfall in the distant future (2070–2099). This situation presents us with two scenarios: (1) global warming only and (2) global warming and increasing aridity. From recent changes in Sahel rainfall, we take a neutral position and assume both are plausible scenarios.

Finally, to feed GCM-derived information into the environmental and biophysical model used in this study, monthly data are transformed into daily values by interpolation and statistical modeling (Richardson, 1981; Racsco et al., 1991).

4.2 Socioeconomic scenarios

The upper envelope of population projections with different growth models (Njie, 2002b) is used in this study. This corresponds to the cohort survival method that assumes a decline unchanging fertility rates. Rural to urban population ratio, currently 50:50, is

assumed to evolve linearly over time to 20:80 by the end of the century. In this scenario, however, absolute decline in rural population will occur late in this century. Bolstered by food security and poverty alleviation policies, agricultural production is, therefore, expected to be a dominant factor in the economy.

Land availability, a crucial factor in cereal production, is assessed in light of other competing uses—economic, natural/conservation, and residential. Priorities of use, regeneration and degradation rates, together with suitability for agriculture, are also incorporated in the land availability calculus. In like manner, the feasibility of putting 20% of millet production under irrigation is assessed by comparing projected water demand with renewable water resources. The reader may note that 20% irrigation is a benchmark only achieved in developed countries. Population projections, land, and water availability, are shown in Figures 3A–C.

For the adaptation/management strategies analyzed in this study, the issue of significant technological change and innovation is only considered for research and development (R&D) outcomes of regional crop breeding programmes. No major revolution is expected in already mature irrigation technology, but there is room for improvement of water delivery efficiencies. Costs are also likely to change, but projections are not attempted because of large uncertainties and use of constant prices for other variables in the study. Little sophistication is required for fertilizer application.

Public policy in food security and poverty alleviation seeks to “stay ahead of the curve,” so to speak. Policy variables used in this study include per capita cereal consumption of 250 kg/year, based on the upper limit of local production and imports from 1995 to the present (DOP, 2005). One month, but not more than two months food

requirements is prescribed as the strategic food reserves. As already mentioned, we ensure at the problem specification stage that conflicts between land and water management and other policies are eliminated. At the analysis stage, changes in policy variables, and personal choices/food preferences are made to see what impact they might have on economic performance of strategies and food security.

4.3 Crop modelling

In this study, crop yields are simulated with the SWAP-WOFOST model (Feddes et al., 1978; Van Dam et al., 1997; Kroes et al., 1999).

SWAP (Soil-Water-Atmosphere-Plant model) simulates one-dimensional water, solute, and heat transport in saturated and unsaturated soils (Feddes et al., 1978; Droogers, 2000). Figure 4 shows the various components of water and heat transport in SWAP. Rainfall (including irrigation) and solar radiation reaching the soil surface is related to Leaf Area Index (LAI) of the crop. Solute, heat and water transport, governed by laws of mass and energy conservation, is modulated by heat and moisture transmission and storage properties, concentration, temperature and pressure gradients, and fluxes at boundaries of study domain.

Whereas precipitation is generated from downscaled GCM model outputs, irrigation amount and scheduling is specified by the analyst/user. Irrigation is triggered by soil in the root zone drying beyond a critically low value. The Penman-Monteith equation is used to compute evapotranspiration, that is, the sum of evaporation and transpiration streams. For crops with close canopies, or densely planted crops, soil evaporation decreases, but transpiration increases as crop development progresses.

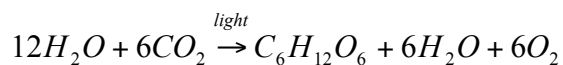
Density of foliage, characterized by the LAI, decreases rainfall and radiation directly reaching the soil surface.

Water not retained within the unsaturated zone, or taken up by the crop in place, flows to adjacent drains, groundwater, or drains freely, according to the boundary conditions specified by the analyst/user. Runoff is generated when surface infiltration or storage capacity is exceeded. SWAP is linked to WOFOST through water and nutrient uptake by crop roots and LAI. Crop water uptake is directly related to soil wetness, potential evapotranspiration, and root length.

Soil temperature exercises some influence on bioavailability of nutrients, and less so on water dynamics, especially when the crop in place has a well-developed root system. Essentially isothermal at depths below 100 cm, the soil temperature regime depends on surface heating, soil thermal properties, and wetness. Estimates of soil properties used in the study are obtained from the literature (Williams, 1979; Campbell, 1985; FAO, 2002).

WOFOST (the WORld FOod STudies model) simulates the phenological development of a crop from emergence to maturity on the basis of the crop's genetic attributes, and environmental conditions (Supit et al., 1994; Spitters et al., 1989). Figure 5 shows the main processes simulated by WOFOST, in particular, the partitioning of assimilates from photosynthetic activity into root, stem, leaves, and storage organs.

In photosynthesis, CO₂ from the air is transformed into glucose (C₆H₁₂O₆), according to the well-known process:



The energy for this transformation originates from (sun)light, or, more precisely, from the photosynthetically active radiation (PAR). Part of the glucose produced is used to provide energy for respiration and crop maintenance, depending on the amount of dry matter in the various living plant organs, the relative maintenance rate per organ and the temperature. The remaining assimilates are partitioned among roots, leaves, stems, and storage organs, in fractions depending on the phenological development stage of the crop. Time-dependent partitioning coefficients change with crop development stage (Van Diepen et al., 1989). For a grain crop such as millet, the dry weight of storage organs, on an areal basis, at the end of the crop cycle equivalent to crop yield (kg/ha) is an important model output.

The net increase in leaf structural dry matter and the specific leaf area (ha/kg) determine leaf area development, and, hence, the dynamics of light interception, except for the initial stage when the rate of leaf appearance and final leaf size are constrained by temperature, rather than by the supply of assimilates. Leaf senescence occurs because of water stress, shading, and also because of life span exceedance. The death rate of stems and roots is related to the development stage and crop genotype. Crop parameters in this study were taken from the literature (de Willigen and Noordwijk, 1987; Van Diepen et al., 1989). Some of these were changed in one of the adaptation strategies to see the impact on yields.

4.5 Economic feasibility analysis

CEREBAL, a simple spreadsheet model, is used to update and compute running totals of cereal stocks in The Gambia. Population size and per capita consumption constitute key

variables on the demand side of the model. Cereal production in any year is obtained by summing up production from rain-fed/irrigated rice with that from upland cereals, the latter derived from SWAP-WOFOST crop yield and cultivated area. Variations in cultivated area are handled through a land-use submodel that incorporates competing land uses within the socioeconomic context of The Gambia. At end of every year in the time window studied, CEREBAL compares demand for cereals/grain with production and computes commercial grain imports/food aid requirement in line with national food security policy.

Economic feasibility of different adaptation options is evaluated from net benefits attributable to, and residual damages associated with a particular adaptation option/strategy. Net adaptation benefits (NAB) is the difference between climate change damages avoided by implementing a particular adaptation option/strategy and its implementation costs. Ideally zero imposed climate change damages (ICCD) are measured, but sometimes, ICCD measures residual damages in spite of adaptation actions. NAB and ICCD relate to the time window studied.

5. Results and Discussions

Economic performance of selected adaptation/management practices is assessed through an iterative procedure, in which socio-economic and future climate scenarios are modified and impacts are analyzed.

In the preceding discussion on SWAP-WOSFOST, it is clear that climate is one of the key determinants of crop yield. The importance of adaptation/management practices is also implied, especially for irrigation. Climate change impact on crop production is assessed by comparing baseline yield statistics from the reference period with those

projected for the near and distant futures, under a business-as-usual scenario, that is, a low-intensity rain-fed agricultural production system. In a stepwise approach, we first present simulated crop yields under different management strategies and climate projections in section 5.1. Economic feasibility of selected adaptation practices is treated in section 5.2

Discussions revolve around changes in key variables, and their impacts on economic performance of adaptation strategies and food security.

5.1 Crop yields

In the preceding discussion on SWAP-WOSFOST, it is clear that climatology is one of the key determinants of crop yield. The importance of adaptation/management practices is also implied, especially for irrigation.

5.1.1 Yield under present and future climate

Statistics of simulated yields presented in Table 1 reveal a systematic element of dependence on climate scenario. This is hardly surprising, especially in the case of distant future simulations with HadCM3, which we recall prescribes a 400-mm decrease in rainfall relative to the period 1961–1990.

In the near future, ECHAM4 and HadCM3 alike suggest an increase in average yields, but also, an increase in interannual variability with time. Increasing yields could possibly be explained by CO₂ fertilization and shift in the climate toward optimum temperature for C₄ crops (Wand et al., 1999). An 8% relative decrease in rainfall under HadCM3 seems, however, to counteract these favorable conditions, as reflected in the percentage increase in the coefficient of variation (CV).

The complex relationship between climate variables and crop yield is also apparent in the statistics for the reference period. In Table 1, yield statistics obtained from historical climate lie somewhere between corresponding values for ECHAM4 and HadCM3, even though ECHAM4 simulation of reference period climate give a slightly higher average rainfall and smaller CV. A plausible explanation to this unexpected result may, similar to irrigation scheduling, have to do with the timing and amount of precipitation prescribed in the model computations. Observe that yield statistics in this table correspond to a business-as-usual scenario, that is, millet cultivation under rain-fed conditions, and no changes in management/crop husbandry practices. The business-as-usual scenario is very unlikely but serves a useful purpose in the analysis that follows.

5.1.2 Yield under different adaptation practices

Combining the improbability of the business-as-usual scenario with farmers' proactive response to environmental changes, we introduce changes in SWAP-WOFOST that reflect better water control, crop selection, and soil fertility management. As previously mentioned, there is nothing revolutionary about such an approach. The technology to implement some strategies already exists but has not been fully harnessed. In the near-to-distant future, one may also expect improved cultivars from crop breeding programs.

Mimicking the outcome of selective breeding and genetic engineering programs, we make changes to the following attributes of *P. typhoides*: (1) increased drought tolerance, (2) increased yield, and (3) shorter growing cycle to see the impact on yields. The best results, indicated by a combination of the highest mean and lowest CV,³ are

shown alongside results corresponding to crop fertilization and irrigation in Tables 2A and 2B. Yield statistics in these tables permit (1) a comparison of business-as-usual approach to different adaptation strategies and (2) intercomparison of adaptation strategies for the purpose of performance ranking.

For the period 2010–2039, average yield increase, with adaptation, by 13 to 43%, and 13 to 37%, under ECHAM4 and HadCM3 projected climates, respectively.

Interannual variability across both models, which decreases by 84 to 200%, also presents a remarkable stability in yields. For smallholder farming households, stability in yields is one important aspect of poverty and survival. The consequences of a poor harvest year are not so devastating if the following year gives a normal harvest. Periods of two or more successive years of poor harvest, however, are rather difficult to overcome without external assistance.

Statistics in Table 2B, relating to the distant future (2070–2099), are somewhat more nuanced. For the strategies analyzed, ECHAM4 projections exhibit a relative change in the average yield of between –12 and +36%. In contrast, simulations based on HadCM3 projections show an increase of 64 to 411%, depending on the adaptation strategy/management practice simulated. Notice, however, that higher fertilizer and water inputs are needed to achieve the results in Table 2B. Waterlogged conditions caused by overirrigation indeed explain the 12% drop in yield relative to do-nothing/business-as-usual response under ECHAM4. Because water is a limiting constraint under HadCM3 projections for the distant future, it is hardly surprising also that CV drops by an order of magnitude when 500 mm of irrigation water is delivered to the crop. This, in essence,

more than compensates for the HadCM3 drop in mean annual rainfall, relative to the reference period (1961–1990).

In general, as crop yields increase, interannual variability also decreases, under all adaptation options. Using the criterion of lowest CV, irrigation, except when it is overdone, outranks other adaptation options. In the remainder of this paper, a pairwise comparison of its economic performance is made with crop fertilization, ranked second best adaptation option.

5.2 Economic performance of selected adaptation practices

Economic analysis presented in this paper uses costs and benefits of adaptation strategies within a national cereal self-sufficiency/import substitution framework. Key variables in the analysis include the cost of inputs, market price of cereals, consumer preferences, and food security policy. A number of assumptions are also introduced to deal with uncertainties in some of the variables. The few general assumptions are as follows:

- (i) cultivated area of millet increases proportionally with population growth, subject to a 0.15 ha/capita limit in order to avoid conflict with other competing land uses;
- (ii) food imports/aid is triggered by buffer stocks falling below a critical stock-to-utilization ratio (STU); and
- (iii) food import/aid costs are expressed in constant dollar values.

We further assume that economic agents with a central role in climate change adaptation, that is, traders and *dabadas*, respond to market signals in a rational way that is

influenced by government regulation, taxation, incentives, and other economic instruments.

5.2.1 Crop fertilization

Further assumptions specific to crop fertilization include the area over which the measure is applied and the rate of application. It is obvious that both variables have consequences on farm budgets but are also potentially rewarding insofar as fertilization improves crop yields (see Tables 2A, and 2B).

Table 3 gives a number of economic indicators of performance of crop fertilization, assuming that 100 kg/ha of nitrogen fertilizer is applied to the entire area under millet cultivation. Per capita cereal consumption, closely matching current levels is set to 250 kg/person/year (DOP, 2005).

Visual inspection of net adaptation benefits (NAB) clearly indicates the economic potential of fertilization as an adaptation option in the near future. Positive NAB into the distant future also reinforces the evidence of economic viability under a changing climate. Climate change damages (CCD) reflects the dollar value of production shortfalls, if no adaptation measure is deployed. In essence, this is equivalent to commercial import of cereals and/or food aid required to maintain food security at a national level. With adaptation, residual damages, hereafter referred to as imposed climate change damages (ICCD), is the difference between CCD and NAB. A positive ICCD, such as the ones that appear in Table 3 indicate that fertilization alone is not sufficient to make up for cereal production shortfalls, under the combined effect of climate and demographic changes.

Sensitivity of results in Table 3 to the percentage area treated with fertilizer is analyzed by changing this fraction to several values between 5 and 100%, without qualitative changes to the results.

STU is an important food security variable, especially when natural hazards or disruption of supplies are anticipated. Results of increasing STU shown in Table 3 are, however, ambivalent. An increase in ICCD in response to an increase in STU in the near future could be seen as a misallocation of resources. With higher interannual variability, however, increased STU seems to have a positive payoff by stimulating an increase in NAB from 17 to nearly 95 million U.S. dollars.

In the long run, especially when individuals' economic situations improve, it is reasonable to assume change in peoples' food preferences. For the distant future, therefore, we posit, and analyze the impact of a shift in food choices, marked by a reduction in cereal consumption. Observe that reducing consumption to 175 kg/person/yr does not imply food rationing but simply reflects a change in dietary habits, born out of improved economic status. Whether reduction in per capita cereal consumption confers economic advantages is not obvious from Table 4. Only at an STU of 20% in near future can one speak of a clear advantage. Note, in particular, the relative changes in ICCD and per capita consumption.

5.2.2 Irrigation

Other assumptions specific to irrigation include the area over which the measure is applied, as well as the rate of expansion, irrigation intensity, and rice yields under irrigated conditions. Assumptions prescribed for the analysis are as follows:

(1) irrigated area of coarse cereals increases linearly with time, from its current value of 2-20% by end of the 21st century; (2) rice irrigation from surface water is accelerated after commissioning of Sambangalou dam; (3) rice yields increase to 4 metric tons/ha under controlled irrigation; and (4) irrigated millet and rice are harvested twice a year.

Table 5 shows a number of economic performance indicators under irrigated conditions. A major point of observation in this table, concerning the near future (2010–2039) is the negative NAB. This clearly spells out that resources could be more efficiently allocated to procurement of food supplies on the world grain/cereal markets. This situation apparently changes in the distant future when water becomes the major limiting factor for crop production. As shown in Table 4, however, economic efficiency of irrigation is related to policy variables like the STU ratio governing cereal imports. Indeed, increasing STU worsens the outcome of the net benefit calculus.

Sensitivity analysis shows that NAB from irrigation only becomes positive when water costs drop below 0.09 USD/m³. Considering, however, that this is 25% less than the unit cost of water in the lowest tariff block of the national water undertaker, it is extremely unlikely that smallholder irrigation schemes can achieve economies of scale sufficient to bring down water costs to a profitable level. It suffices to point out that operation and maintenance (O&M) account for 80–90% of pump irrigation costs and how this fraction evolves would depend on future world energy markets, technological innovation, and state of the Gambian economy.

An oblique approach to the problem of cost reduction is how to increase the market value of crops harvested. The conundrum essentially reduces the number of choices of crops. High value, nonfood (e.g., flowers), nonstaple crops (e.g., vegetables)

currently fetch higher prices than cereals on the market, but on the scale of production, envisaged, this may no longer be the case. The problem, however, does not have to be articulated in such dichotomous terms. What one probably needs is to find an optimal mix of crops fetching the highest economic returns, subject to land, water, labor, and other constraints.

Table 6 shows that a decrease in cereal intake from 250 kg/capita to 175 kg/capita, closely matches relative changes in ICCD, except in the near future. At different STU values, reduction in cereal consumption/imports drastically reduces ICCD. One way of interpreting such a reduction is foreign exchange savings if the bill for foreign goods and services relating to the production and/or importation of alternative foods is incorporated into the calculus.

Although economics alone may make crop fertilization/irrigation attractive adaptation strategies in the near and distant future, a commitment to food security, rooted in developing The Gambia's agricultural potential, is indispensable to reducing the country's sensitivity and vulnerability to climate risks. In this regard, it may be quite important to discuss the role of key stakeholders, as well as to examine the conditions under which adaptation options are most likely to be taken up by *dabadas*.

Without any doubt, the government of The Gambia, responsible for social, economic, and related policies, should take the first step to ensure that valid research findings get translated into tangible benefits. Government's role is to pick up research results, demonstrate their validity, and create incentives for integration of the options into current agricultural practice.

Considering, however, the low level of returns on investments in cereal production compared to other crops, it is fair to say that farmers, when given the choice, will opt for irrigation of noncereal crops in the dry season. There is already ample evidence of this in community and women *kafo*⁴ gardens across the country. Even in some lowland environments, noncereal, high-value horticultural crops, such as pepper (*Capsicum annum*), okra (*Hibiscus esculentus*), and tomatoes (*Lycopersicon esculentum*), instead of rice, are grown under irrigation in the dry season. Two reasons may explain this practice. First, part of the incomes generated by households from horticultural production is used to purchase imported rice when their cereal stock gets depleted. Second, and perhaps overlooked, planting decisions also make sense in light of the agronomic practice of crop rotation.

A future government outreach/extension program therefore stands the best chance of success when *dabadas* pursue multiple objectives, including food security. In this scenario, discussed above as an optimization problem, a fraction of the area under full water control could be allocated to noncereals, and part of the extra revenue generated used to expand cereal production in subsequent years. *Dabadas* have a good knowledge of these issues, experience of climate extremes, and a strong stake in harnessing adaptation options to ensure their food security.

From a broader perspective, The Gambia government's national disaster reduction strategic framework, in the making, provides an attractive opportunity to build partnerships for food security. Community empowerment, efficient marketing structures, competitive prices, and price stability are some of the factors that hold the key to the transformation of agricultural production in The Gambia.

6 Conclusions

Crop selection and fertilization, used as insurance against climate variability by smallholder farming households, are proven to be equally effective in offsetting global warming impacts in the near future. The yet untested practice of irrigation gives the highest increase in productivity under different climate projections.

The study reveals that economic efficiency of adaptation options is strongly correlated with unit costs of implementation of a particular option. In this regard, high units costs of irrigation development makes the option less attractive than crop fertilization under specific conditions. Time dependence of efficiencies of adaptation options is also linked to the evolution of future climate. Indeed, irrigation may become an imperative in the distant future if precipitation declines in conformity with the HadCM3 projections, or world cereal markets become seriously affected by conditions in countries with historically surplus production. Large uncertainties surrounding R&D costs of crop breeding makes economic feasibility analysis of this option less tractable.

Essentially, there is no single best adaptation strategy, and instead of import substitution, one should be looking at complementing business-as-usual (i.e., food imports) with fertilization and irrigation of locally grown cereals. In the short-run, expanding crop fertilization, in particular, has significant advantages. It requires no technological sophistication and promises high returns.

These results call for an immediate response from government, the service sector, and the farming community. Notwithstanding, some challenges still remain. Food policy

development and analysis require more sophisticated projections of commodity prices, costing R&D in crop science, technology trends, and their impacts on costs.

Acknowledgments

The research was supported by grant number AF47 from the Assessment of Impacts and Adaptations to Climate Change (AIACC) Project partly funded by the Global Environment Facility (GEF), and the U.S. Environmental Protection Agency (USEPA). The authors wish to thank two anonymous reviewers for their useful comments. The authors also gratefully acknowledge the steady support contributions of AIACC coordinator, Neil Leary, and Malanding S. Jaiteh, Geospatial Analyst at CIESIN, Columbia University (USA).

References

- Campbell, G. S. 1985. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Sci* 117: 311–314.
- Carney, E. 1986. The social history of Gambian rice production: an analysis of food security strategies, Ph.D. thesis, Michigan State University, Ann Arbor, MI, USA.
- Cole, A., Sanyang, K., Marong, A. J., and Jadama, F. 2005. Vulnerability and adaptation assessment of the agricultural sector of the Gambia to climate change. Consultancy Report Prepared for NAPA Project LDL 2328 2724 4699. Banjul, 36 pp.
- de Willigen, P, and van Noordwijk, M. 1987. Roots, plant production, and nutrient efficiency, PhD thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

- DOP. 2001. Statistical Yearbook on Gambian agriculture for the year 2000. Annual Report. Department of State for Agriculture. Banjul. 47 pp.
- DOP. 2003. Statistical Yearbook on Gambian agriculture for the year 2002. Annual Report. Department of State for Agriculture. Banjul. 47 pp.
- DOP. 2005. Statistical Yearbook on Gambian agriculture for the year 2004. Annual Report. Department of State for Agriculture. Banjul. 74 pp.
- Droogers, P. 2000. Estimating actual evapotranspiration using a detailed agro-hydrological model. *J. Hydrol.* 229:50–58.
- FAO. 2002. Digital soil map of the world and derived soil properties on CD-ROM. <http://www.fao.org/ag/agl/agll/dsmw.htm>.
- Feddes R. A., Kowalik P. J. and Zarandy H. 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc. Wageningen, The Netherlands.
- Government of the Gambia. 2003. First national communication of the Republic of The Gambia to the United Nations Framework Convention on Climate Change. Government of The Gambia. United Nations Development Program, Global Environment Facility.
- Gomez, B.E., Njie, M., Jallow, B.P., Hellmuth, M.E., Callaway J. Mac, and Droogers, P. 2005. Adaptation to Climate Change for Agriculture in The Gambia: an explorative study on adaptation strategies for millet. AIACC Draft Working Paper, AF47 Gambia project. Banjul, 60 pp.

- IPCC. 2000. Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change, edited by N. Nakicenovic and R. Swart, Cambridge University Press, Cambridge, UK, 570 pp.
- Jallow, S.S., 1995. Identification of the response to drought by local communities in Fulladu West district of the Gambia. Singapore. *J. Trop. Geogr.* 6:22–41.
- Kroes, J. G., J. C. van Dam, J. Huygen, and R.W. Vervoort. 1999. User's Guide of SWAP version 2.0. Simulation of water flow, solute transport, and plant growth in the Soil-Water-Atmosphere-Plant environment. *Technical Document 48*, Alterra Green World Research, Wageningen, *Report 81*, Department of Water Resources, Wageningen University and Research, Wageningen, The Netherlands, 127 pp.
- NEA, 1997. State of the Environment Report—The Gambia. National Environment Agency, Banjul, 125 pp.
- Njie, M. 2002a. National Water Security in the first half of the 21st Century. Report prepared under GAM/93/003 as a contribution towards Gambia's National Water Resources Management Strategy, UNDP/DWR, Banjul, 24 pp.
- Njie, M. 2002b. Second Assessment Report of Climate Change induced Vulnerability of Gambian water resources sector, and daptation strategies. Report prepared for the Gambia's National Climate Committee, Banjul, 71 pp.
- Racsko, P., Szeidl, L., and Semenov, M. A. 1991. A serial approach to local stochastic weather models. *Ecol. Model.* 57:27–41.
- Richardson, C.W. (1981). Stochastic simulation of daily precipitation, temperature and solar radiation. *Water Resour. Res.* 17:182–190.

- Spitters, C. J. T., H. Van Keulen and D. W. G. van Kraalingen. 1989. A simple and universal crop growth simulator: SUCROS87. In: *Simulation and systems management in crop protection*, edited by R. Rabbinge, S. A. Ward, and H. H. van Laar. Simulation Monographs. Wageningen, Pudoc, The Netherlands, 147–181.
- Supit, I., A. A. Hooijer and C. A. Van Diepen (Eds.). 1994. System description of the WOFOST 6.0 Crop Growth Simulation Model implemented in CGMS. Vol. 1: Theory and algorithms. European Commission, Luxembourg. 146 pp.
- Van Dam, J.C., J. Huygen, J.G. Wesseling, R. A. Feddes, P. Kabat, P. E. V. VanWalsum, P. Groenendijk, and C. A. van Diepen. 1997. Theory of SWAP vers. 2.0. Wageningen Agricultural University and DLO Winand Staring Centre. Technical Document 45.
- Van Diepen, C.A., J. Wolf, H. Van Keulen, and C. Rappoldt, 1989. WOFOST: a simulation model of crop production. *Soil Use Mgmt.* 5:16–25.
- Verkerk, M. O., and van Rens C. P. M. 2005. Saline intrusion in Gambia river after dam construction: Solutions to control saline intrusion while accounting for irrigation development and climate change. Research Report, University of Twente, The Netherlands, 64 pp.
- Ward, S. J. E., Midgley, G. F., Jones, M. H. and Curtis, P. S. 1999. Responses of wild C4 and C3 grass (Poaceae) species to elevated atmospheric CO₂ concentration: a meta-analytic test of current theories and perceptions. *Global Change Biol.* 5:723-741.

Williams, J.B., 1979. Soil Water Investigation in The Gambia. Technical Bulletin 3. Land Resources Development Centre. Ministry of Overseas Development, Surrey, England.

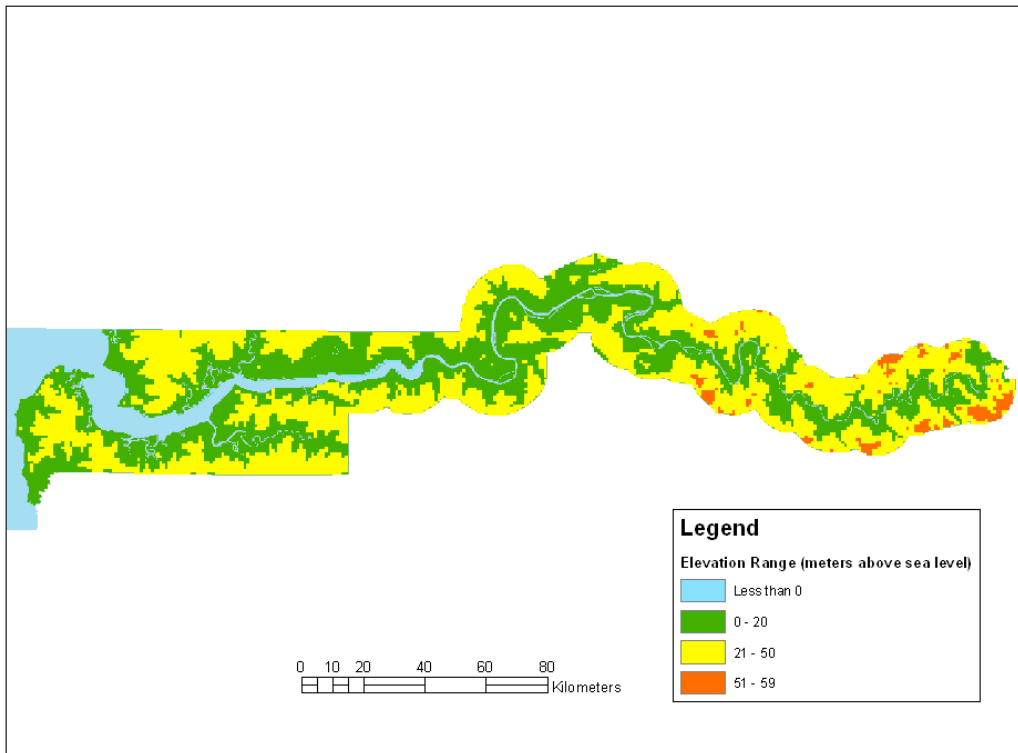


Figure 1. Elevation map of The Gambia (Map prepared by Malanding Jaiteh, CIESIN, Columbia University, using U.S. Geological Survey Digital elevation model, STRM data).

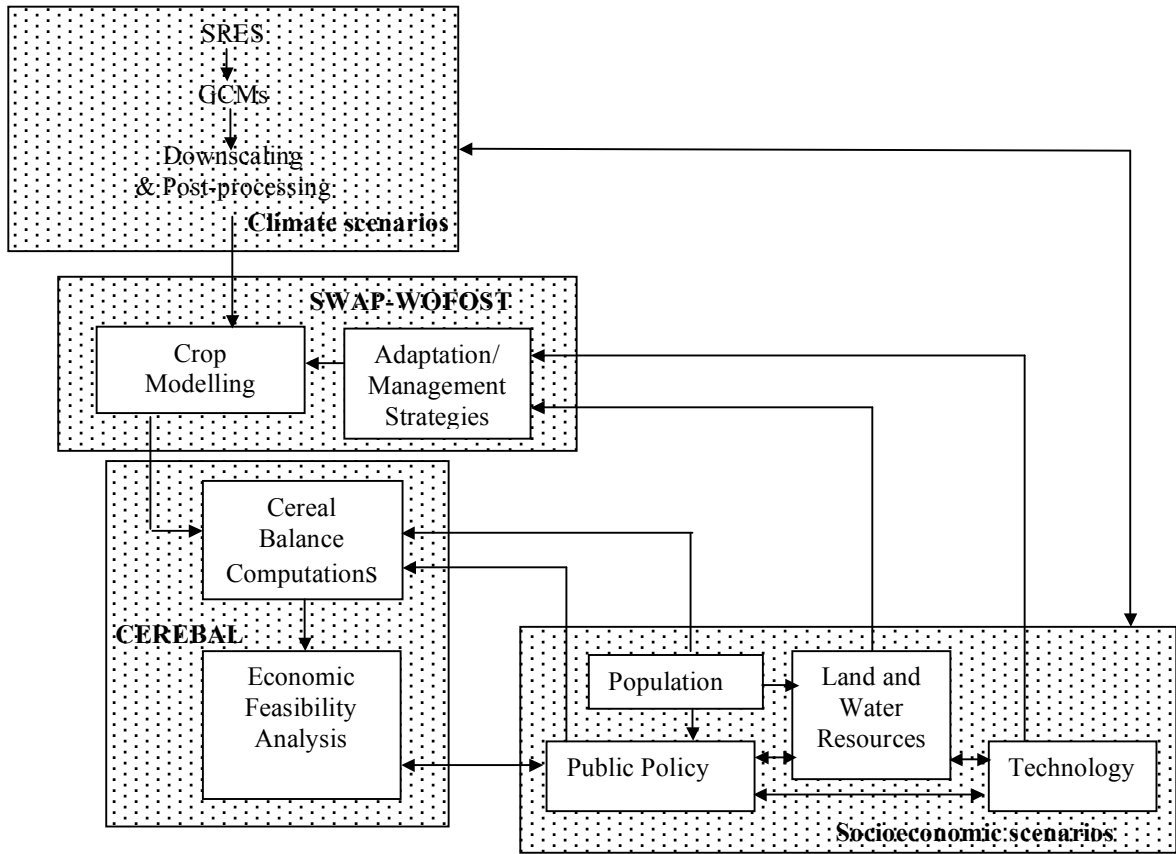


Figure 2. Assessing economic feasibility of climate change adaptation.

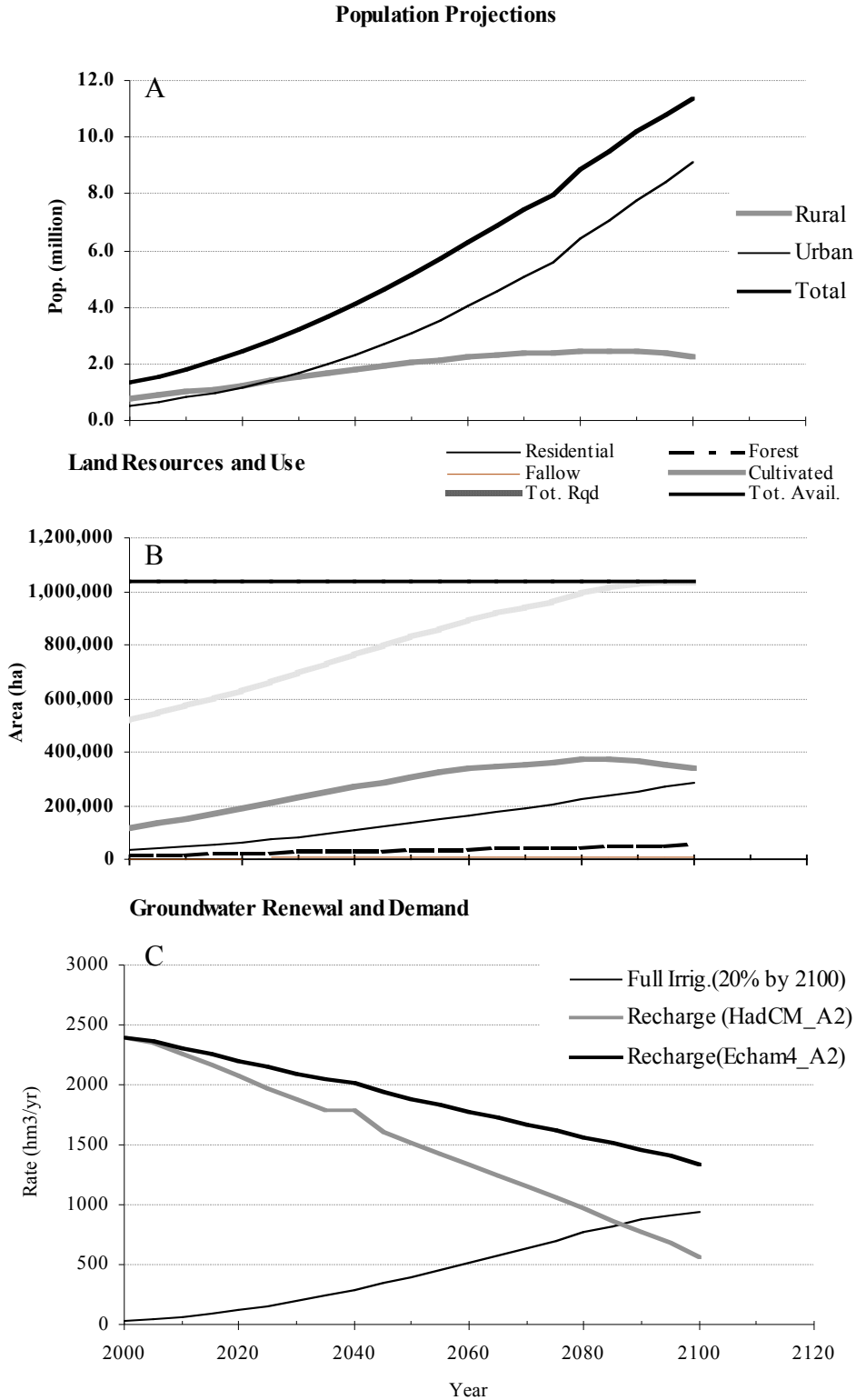


Figure 3. Projections to the year 2100 of population and population distribution (A); land availability and use categories (B); groundwater recharge and irrigation demand under different climate scenarios (C).

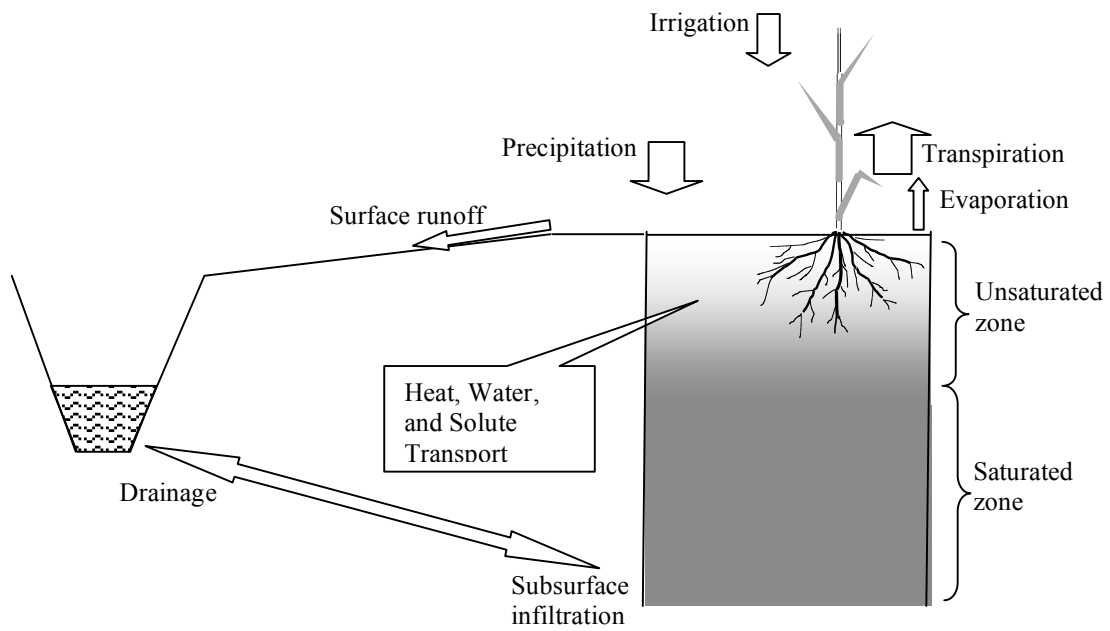


Figure 4 Schematic illustration of water and heat transport processes in SWAP

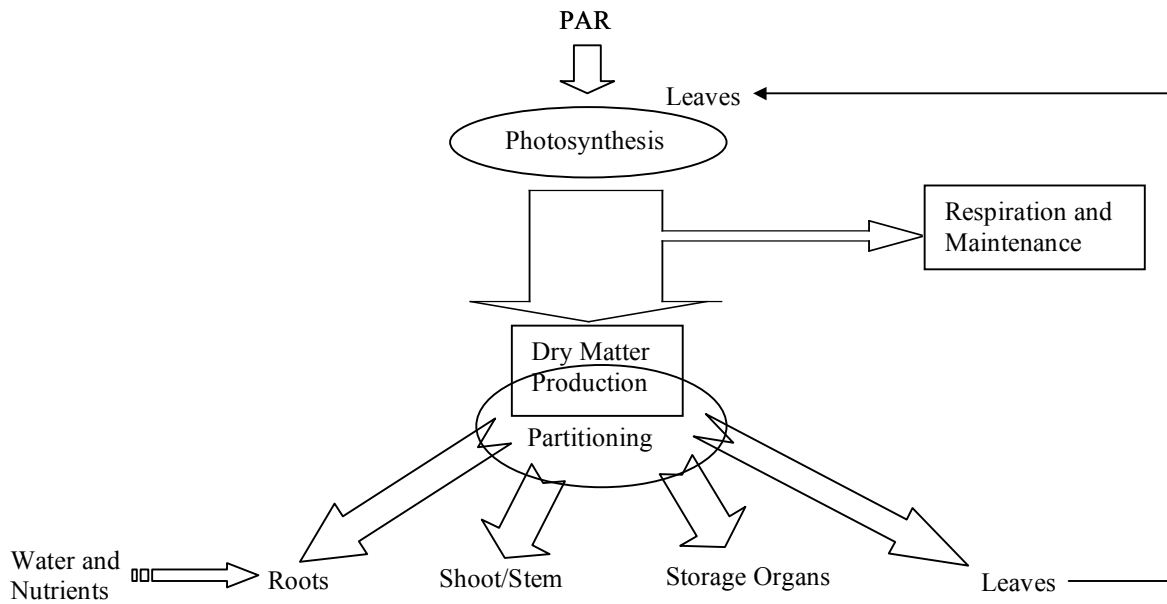


Figure 5. Schematic illustrations of biophysical processes in WOFOST. Photosynthetically Active Radiation is shown as PAR.

Table 1. *Average Annual Millet Yields \bar{x} (kg ha⁻¹) and Variability, CV (%) Under Different Climate Scenarios and Time Periods*

	Historical		ECHAM4		HadCM3	
	\bar{x}	CV	\bar{x}	CV	\bar{x}	CV
Reference period (1961–1990)	1,030	27	923	23	1,115	30
Near future (2010–2039)	–	–	1,046	24	1,141	33
Distant future (2070–2099)	–	–	1,274	29	243	123

Table 2A. Yield Response of Different Strategies for the Period 2010–2039

	ECHAM4		HadCM3	
	\bar{x}	CV	\bar{x}	CV
Adaptation				
None	1,046	24	1,141	33
High-yielding cultivar	1,186	22	1,294	22
100 kg ha ⁻¹ yr ⁻¹ (N)	1,450	20	1,517	25
150 mm yr ⁻¹	1,496	13	1,563	11

Table 2B. Yield Response of Different Strategies for the Period 2070–2099

	ECHAM4		HadCM3	
	\bar{x}	CV	\bar{x}	CV
None	1,274	29	354	167
High-yielding cultivar	1,500	30	583	135
200 kg ha ⁻¹ yr ⁻¹ (N)	1,733	20	610	125
500 mm yr ⁻¹	1,110	32	1,811	13

Table 3. *Cost and Benefits of Fertilization for Two Values of Stock-to-Utilization Ratio*

Period	Economic indicator	STU	
		10%	20%
2010–2039	Climate change damages (USD)	155,085,257	151,858,775
	Adaptation benefits (USD)	37,880,060	28,635,720
	Adaptation costs (USD)	6,287,188	6,287,188
	Net adaptation benefits (USD)	31,592,880	22,348,540
	Imposed climate change damages (USD)	123,492,380	129,510,240
<hr/>			
Period	Economic indicator	STU	
		10%	20%
2070–2099	Climate change damages (USD)	1,049,799,381	1,049,799,381
	Adaptation benefits (USD)	27,980,710	105,377,750
	Adaptation costs (USD)	10,733,488	10,733,488
	Net adaptation benefits (USD)	17,247,230	94,644,270
	Imposed climate change damages (USD)	1,032,552,160	955,155,120

STU, stock-to-utilization. Computations are based on HadCM3 climate projections. All values relate to an average calendar year. Cereal prices at constant dollar values are USD150 per metric ton.

Table 4. Comparison of selected economic indicators for crop fertilisation different per capita cereal consumption

2010–2039	STU = 10%		
	[1]	[2]	[2]/[1]
Per capita consumption (kg/person/year)	250	175	0.700
Adaptation benefits (USD)	37,880,060	22,945,711	0.606
Imposed climate change damages (USD)	123,492,380	45,722,285	0.37
	STU = 20%		
	[1]	[2]	[2]/[1]
Per capita consumption (kg/person/year)	250	175	0.700
Adaptation benefits (USD)	28,635,720	30,290,700	1.058
Imposed climate change damages (USD)	129,510,240	24,003,512	0.185
2070–2099	STU = 10%		
	[1]	[2]	[2]/[1]
Per capita consumption (kg/person/year)	250	175	0.700
Adaptation benefits (USD)	27,980,710	68,966,071	2.465
Imposed climate change damages (USD)	1,032,552,160	637,015,798	0.617
	STU = 20%		
	[1]	[2]	[2]/[1]
Per capita consumption(kg/person/year)	250	175	0.700
Adaptation benefits (USD)	105,377,750	29,990,264	0.285
Imposed climate change damages (USD)	926,443,911	678,001,168	0.732

Table 5. *Cost and Benefits of Irrigation for Two Values of Stock-to-Utilization Ratio*

Period	Economic Indicator	STU	
		10%	20%
2010–2039	Climate change damages (USD)	155,085,257	151,858,775
-	Adaptation benefits (USD)	43,318,700	36,462,950
-	Adaptation costs (USD)	124,486,314	124,486,314
-	Net adaptation benefits (USD)	-81,167,620	-88,023,370
-	Imposed climate change damages (USD)	236,252,880	239,882,150
<hr/>			
Period	Economic indicator	STU	
		10%	20%
2070–2099	Climate change damages (USD)	1,049,799,381	1,021,088,181
-	Adaptation benefits (USD)	303,186,300	207,496,720
-	Adaptation costs (USD)	251,163,626	251,163,626
-	Net adaptation benefits (USD)	52,022,680	-43,666,910
-	Imposed climate change damages (USD)	997,776,710	1,064,755,100

All other conditions underlying results in Table 3 remain unchanged.

Table 6. *Comparison of Selected Economic Indicators for Irrigation and Different per Capita Cereal Consumption*

2010–2039	STU = 10%		
	[1]	[2]	[2]/[1]
Per capita consumption (kg/person/year)	250	175	0.700
Adaptation benefits (USD)	43,318,700	31,525,572	0.728
Imposed climate change damages (USD)	236,252,880	37,142,424	0.157
	STU = 20%		
	[1]	[2]	[2]/[1]
Per capita consumption(kg/person/year)	250	175	0.700
Adaptation benefits (USD)	36,462,950	36,178,597	0.992
Imposed climate change damages (USD)	239,882,150	38,472,143	0.160
	STU = 10%		
	[1]	[2]	[2]/[1]
Per capita consumption(kg/person/year)	250	175	0.700
Adaptation benefits (USD)	303,186,300	242,362,650	0.799
Imposed climate change damages (USD)	997,776,710	704,049,370	0.706
	STU = 20%		
	[1]	[2]	[2]/[1]
Per capita consumption(kg/person/year)	250	175	0.700
Adaptation benefits (USD)	207,496,720	245,876,300	1.185
Imposed climate change damages (USD)	1,064,755,100	702,545,280	0.660

¹ Dabada: Framing household comprising individuals, usually related, who pool their resources together and conduct work activities (farming and nonfarming) as a unit (DOP, 2005).

² SRES A2 Scenario: High population growth, economic growth regionally oriented, technological change and per capita gains fragmented.

³ For any two simulations with marginal difference in average yield, the one with a smaller CV is reported in the tables

⁴ kafo: Association in *Mandinka*, one of the languages spoken locally in The Gambia and Senegal, and linguistic cousin to Malinke, in Mali; Dioula, Bukina Faso, and the Ivory Coast.